Technical Paper No. 13

Prediction of Building Debris for Quantity-Distance Siting

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List of Figures

1.0 Predictive Model as a Siting Tool

An analytical model is presented to predict hazardous building debris distances for accidental explosions within explosives material operations buildings. The model was developed for the U.S. Department of Energy (DOE) Safety Office under funding by DOE and the U.S. Department of Defense Explosives Safety Board (DDESB) to provide an approved method for determining siting distances for explosive loading conditions and building construction types most common to DOE facilities. It can be used to predict hazardous debris distances using similar loading conditions in buildings constructed of reinforced concrete, masonry (clay tiles or concrete masonry units), lightweight components such as corrugated metal, or a combination of these materials. Thus, the model is useful to both the DOE and the Department of Defense (DoD) explosives safety community. Verification and refinement of the model are based on data from an extensive test program. The analytical model is a flexible, component based predictive tool, verified with data, which can be used to site explosives operations according to predicted hazardous debris distances. The model is intended for general use within the constraints discussed in Section 1.3.

1.1 Background

Since July 1984, separation distances for DOE explosives handling facilities have been based on both fragment and overpressure criteria in Reference 1. Inhabited building distance criteria for debris is 670 feet for explosives quantities up to 100 lbs and 1,250 feet for quantities greater than 100 lbs up to 30,000 lbs, unless required protection at lesser distances can be demonstrated. This July 1984 change caused great concern at many explosives material facilities. Some separation distances based on debris exceeded plant boundaries or distances between existing structures. Efforts to comply with the criteria involved reduction of explosives material amounts, expansion of plant real estate, or hardening of structures (including the erection of barricades). In several cases, exemptions proved necessary. However, the use of exemptions is an undesirable solution to the problem. Since a typical DOE facility houses relatively small quantities of explosives material, as compared to a DoD facility, the DOE safety community decided to question the broad-ranged DoD fragment separation criteria.

A comprehensive testing program was implemented to develop an analysis method which could be applied with a high level of confidence. Data needed to determine the quantity-distance (Q-D) requirements for combinations of structure and explosive configurations found at DOE facilities were gathered in an extensive test program (Reference 2). The program concentrated on the lower charge amounts and building types common to DOE. The two main objectives of the program were:

- the development of a predictive model to determine hazardous debris distances for accidental explosions in common DOE structures, and

- the calibration and validation of the predictive model using data from component tests of construction materials and explosive amounts of interest for DOE facilities.

Debris criteria for inhabited building distance require that the minimum distance for protection from hazardous fragments will be that distance at which fragments, including debris from structural elements of the facility or process equipment, will not exceed a hazardous fragment density of one hazardous fragment per 600 square feet. It further states that if this distance is not known, the distances of 670 and 1,250 feet described in Section 1.1 will be used *unless one can show by analysis or testing approved by DDESB that a lesser distance meets the criteria.* The model described in this paper provides an approved procedure for conducting such an analysis for building debris. The siting criteria have been modified to include the use of the model by specifically referencing this paper as an example of an approved analysis. Primary fragments and fragments from process equipment may also need to be considered when analyzing a building for siting distances. When hazards from these fragments are considered, one significant source of guidance for predicting their hazardous fragment distances can be found in Reference 3.

1.2 General Model Description

The predictive model is a combination of steps to determine hazardous debris distance and, thus, acceptable siting distance between explosive handling facilities and inhabited buildings. The key steps involve the use of computer codes for predicting internal loads and debris dispersion. The dispersion code has been extensively modified based on the analysis of data from the supporting test program described in Reference 2. Other intermediate steps consist of making prescribed calculations which are based on statistical analysis of the test data and observations from the tests. These calculations are necessary to determine input for the computer codes.

The predictive model follows a component based analysis procedure. The procedure includes the general steps listed below:

- loading prediction on internal surfaces,
- prediction of component breakup and determination of debris characteristics (mass, velocity, angle, drag),
- debris dispersion, and
- debris tumble after impact (ricochet and roll).

The analysis approach and general description of each of these steps is given in this section. Three computer codes and calculations necessary to establish input for these codes make up the model. More explicit steps on how to use the model are provided in Section 2.1. Complete documentary details can be found in Reference 2.

1.2.1 Loading Prediction on Internal Surfaces

The first step in using the model is to define the threat in terms of the charge amount and location and the wall and roof components of the donor structure. Once the explosive threat and building characteristics have been established, the second step of the model is to determine internal loads on each component. Blast loading inside a confined space can be characterized by an initial shock phase which is usually followed by a gas or quasistatic phase loading. The shock phase consists of very short duration, high pressure pulses which load surfaces as the shock reverberates within the donor bay. The magnitude of the shock phase depends on the charge amount, the distance to the loaded surface, and the location of nearby reflecting surfaces. The magnitude and duration of the quasistatic phase depend on the charge amount, the donor bay volume, and the available vent area and mass of vent covers. If the vent area is sufficiently large and the vent cover mass is small, the gas phase is essentially eliminated.

Two types of shock loading are considered by the model -- close-in and far-range loading. Close-in loading occurs when the charge is so close to the component that the applied pressures locally overwhelm its strength. The component loses all structural integrity, and the maximum wall motion is determined by the maximum applied impulse. Far-range loading occurs when the charge is far enough from the wall so that basic structural integrity is maintained, and the wall responds to an average, more uniform load. The wall material properties are also important in determining the load distribution. This is discussed in Reference 2. The use of model procedures for determining close-in loading is limited to situations where the scaled standoff between the charge and the component is between 0.5 and 1.0 $ft/lb^{1/3}$. All greater standoffs will be considered far-range shock loading.

To completely cover the full range of loading conditions possible in an explosive handling building, several combinations of shock loading and quasistatic loading are treated by the model. The loading realms addressed include close-in loading, combined close-in loading and quasistatic loading, far-range loading with quasistatic loading, and far-range loading without significant quasistatic loading. The procedures for predicting loads for each of these realms are included in the step-by-step guidelines in Section 2.1. Only a brief discussion of the tools and methods used to calculate the loads is provided here. Complete details of the reasons for selecting each method and the test data on which they are based can be found in Reference 2.

The SHOCK and FRANG computer codes are used to determine the shock and gas impulse on all components in the donor structure. A combination of the impulse predicted using both codes is used to calculate maximum debris velocity (and several other debris characteristics related to velocity) for debris resulting from each loading realm discussed in this section. The only exception is close-in loading with no quasistatic loading, for which only the SHOCK predicted impulse is used. The model procedures prove to be an accurate treatment of the load based on comparisons to the test data listed in Reference 2. SHOCK is based on a program originally written by Ammann & Whitney. The version currently used in the model (Version 1.0) was acquired from the Naval

Civil Engineering Laboratory (NCEL). This version or the version used at Waterways Experiment Station is acceptable for use in the model. It is used to predict average shock phase loading on internal surfaces including the shock reflections off nearby surfaces. The program includes a reduced area option which allows determination of average shock impulse over a portion of a wall surface or at a single point on the wall. Thus, loads over the entire component, over a local area, or at a point directly across from the charge can be determined. If a building has an exterior ramp or corridor which can also contribute to the debris hazard, the loads on these structural elements are determined using peak reflected air blast curves and the line-of-sight distance to the element. The impact distances determined for these debris are then added to the total debris dispersal predicted for the affected direction. Any quasistatic impulse caused by a detonation in a confined building is predicted using the computer code FRANG. Version 1.0 of this code was also acquired from NCEL and is the code which was used to generate the design charts for internal gas pressure in Volume II of Reference 4.

1.2.2 Building Component Breakup and Debris Characteristics

Component breakup is predicted based on the applied load and the component type. Several debris characteristics are necessary as inputs to the computer code used in the model to determine debris dispersion. Brief descriptions of the main parameters and the methods used to calculate them are presented here. Specific guidelines for determining these parameters are included in Section 2.1. Detailed descriptions of the analysis and the data used to establish the prediction methods can be reviewed in Reference 2.

High speed film coverage of both the response of the walls and the manner in which debris left the test fixtures provided data on component breakup and debris flight and impact characteristics. The extensive debris recovery effort provided data on debris size. These data were used to refine the model procedures for determining characteristics for debris from reinforced concrete, unreinforced masonry, and lightweight metal walls. The following parameters are based directly on test data:

- average debris mass
- total destroyed mass of a wall
- initial angles at which debris leave a wall
- wall breakup (two or three dimensional)
- debris roll and ricochet upon impact
- debris velocities.

Other characteristics such as drag coefficients are based on adapting the work of previous researchers. Wherever possible, statistical analysis provided the basis or verification of input recommendations for the debris dispersion code. All pertinent statistical correlations and complete data summaries are documented in Reference 2.

The breakup is predicted to provide input in a form compatible with the computer code MUDEMIMP used for debris throw. This code, which is discussed in Section 1.2.3, estimates the hazardous debris distance for each component of a building using input probability distributions to describe building breakup. Probability distributions for the following debris parameters are input into the code:

- initial debris velocity
- debris mass
- initial debris trajectory angle
- debris drag coefficient
- debris drag area factor.

The choice of input probability distribution to use for each of these parameters is based on statistical correlations with the test data. Statistical sampling of the measured data for mass, velocity, and angle for each test (including goodness of fit tests on each parameter) established the distributions to be used for these parameters. The recommended distributions are summarized in Sections 1.2.3 and 2.1. Section 2.1 also contains explicit guidelines for calculating each parameter.

1.2.2.1 Debris Velocity

Average initial debris velocity and the initial velocity standard deviation are required inputs in the debris dispersion code used in this model for all component materials except steel beams. Both of these parameters are calculated from the maximum debris velocity. The calculation method for maximum debris velocity depends on the loading realm being considered (see Section 1.2.1) and the component material. Basically, the most accurate method known by the user to obtain the load for a particular charge configuration should be used. The load calculations described in this paper are based on test data using bare spherical charges, the type of charges on which the SHOCK and FRANG codes are based. If another more accurate and approved method is used to determine loading, the user may proceed to step 4.C (page 21) to calculate the maximum velocity using the more accurate loading. If the SHOCK code is used to obtain impulse, the user is automatically assuming a spherical charge and, therefore, must follow the whole procedure in step 4, including using the impulse reduction factor, R_f, described in the next paragraph.

The maximum velocity calculation is the quotient of the total relevant impulse divided by the mass per unit area of the component. The determination of impulse is the most complicated part of the procedure, but it has been outlined in detail in step 3 of Section 2.1. The total relevant impulse is the sum of the relevant shock impulse and the relevant quasistatic impulse (if any). The relevant shock impulse for close-in loading of concrete and masonry components is the predicted shock impulse divided by a reduction factor which is based on the data collected as part of this program. The equations for determining the reduction factor, R_f, (Equations 3 - 6) and the stepwise progression through the velocity calculations (Equations 7 - 17) are outlined in step 4 of Section 2.1. The relevant shock impulse for far-range loading (Equation 8) is equal to the shock impulse predicted as described in Reference 2 and summarized in Section 2.1. An existing curve-fit is used to predict maximum beam velocity (Equations 14 and 15). For all loading of metal panel walls, for far-range shock loading of components of all materials, and for all loading not predicted using the SHOCK code described in this paper, no reduction factor is used.

1.2.2.2 Debris Mass

The average debris mass and the total destroyed mass are required inputs for the MUDEMIMP dispersion code. Both are determined based on test data described in Reference 2. Although the MUDEMIMP code refers to these parameters as masses, they are actually weights which are then converted internally by the code to masses. Thus, the calculations prescribed by the model are actually calculations of debris weight and destroyed weight of a component. The average debris weight for concrete and masonry debris is determined as the product of a volume, the density of the material, and a multiplication factor based on curve fits to test data. The recommended volume and factor for reinforced concrete and unreinforced masonry are given in Equations 19 to 21 in step 5 of the guidelines in Section 2.1. This average "mass" is used with the total destroyed mass of the component to define an exponential distribution of masses for concrete and masonry components. A uniform mass distribution is recommended for metal wall panels varying from 1/4 the panel mass (Equation 24) to the full panel mass (Equation 23) based on observations from two tests conducted during the DOE/DoD test program and on limited accident data. Beams are assumed to fail as a single piece of debris. Thus, a constant mass distribution is used for beams with an input value equal to the total beam mass (Equation 22). The average masses and distributions recommended for each type of component are summarized in steps 5 and 8 of Section 2.1.

The total mass of the portion of the component which is destroyed is required as input to the MUDEMIMP code (along with the average debris mass) to define the distribution of debris masses. It is also used to adjust the number of simulations to obtain an accurate number of debris expected from the accident being simulated. Like average debris mass, this parameter is input in the code as a weight and then converted internally. The value used for this parameter is actually an effective destroyed weight and not necessarily the total weight expected to be destroyed. The recommended value is based on data from tests in which debris which impacted very close-in to the wall were not included in the data collection. These debris do not set either the maximum debris distance or the hazardous debris distance and, thus, were ignored in the analysis. They certainly are a real part of the actual total destroyed weight, but since the calculation procedure is based on test data which excludes those debris, the input value for this parameter should be considered an effective destroyed weight instead of a total destroyed weight.

The total effective destroyed mass for concrete and masonry debris is calculated using linear relationships developed using test data (Reference 2). The total measured debris mass, within the limits of the test data and the collection criterion used, proved to be linearly related to the maximum measured debris velocity for close-in loading. Total debris mass, excluding large pieces, is relatively constant with maximum debris velocity for concrete tests with large quasistatic loading. Thus, for close-in loading of concrete and masonry components, the linear relationships are extrapolated to 1.0, or a total effective destroyed mass equal to the total wall mass. For concrete tests dominated by large quasistatic loading, the total effective destroyed mass is always taken as one-tenth of the total wall mass. The total wall is assumed to be destroyed for lightweight metal walls and lightweight brittle walls. An entire beam is assumed to fail if a non-zero velocity is calculated with the model. Only the most highly loaded beam is considered because a single, whole beam is assumed to cause a hazardous debris density due to the large size of beams. Equations 25 - 29 in step 6 in Section 2.1 summarize the calculation procedure for total destroyed mass for each material type.

1.2.2.3 Debris Trajectory Angle and Drag Effects

The debris trajectory angles to be used in the dispersion simulation are normally distributed. A normal distribution of angles is recommended based on statistical sampling of the vertical angles measured in the DOE/DoD funded test series (Reference 2). The mean of the normal distribution should always be the normal to the surface measured relative to the horizontal. For most walls, this angle would be 0 degrees. For a roof with no slope, this angle would be 90 degrees. The normal for a sloped roof depends on the degree of slope. The standard deviation should be either 1.3 degrees or 10 degrees, depending on the restraint of the wall or roof, the loading realm, and the material type of the component. The limits to be used for specific combinations of these parameters are listed in step 8 of the procedure outlined in Section 2.1. Although some combinations, such as far-range loading of concrete walls restrained at the roof, were not tested, conservative limits were determined. For example, a careful examination of the horizontal spread of debris from a wall which was restrained on the sides (not at the roof) provided the limits to be used for the loading cases in which the roof is restrained.

The trajectory angles for light metal walls and light brittle walls are assumed to be the same as those discussed above for masonry and concrete tests (normal distribution with mean = normal to the surface and standard deviation = 1.3 degrees or 10 degrees). Predictions for the two lightweight metal walls tested for the DOE/DoD program, which were made assuming the trajectory angle distribution described above for walls not restrained at the roof, conservatively predicted the measured maximum debris range. For beams, a constant trajectory angle equal to the normal to the wall or roof from which the beam originates should be used. The previously mentioned conservative debris range predictions made for beams from walls in two half scale tests were made assuming a trajectory angle of 0 degrees.

Drag effects are accounted for in the MUDEMIMP code with a drag coefficient and a drag area factor, the "k-factor". The drag area is the product of the drag area factor and the "base" presented area which is calculated for each debris from the debris mass, density, and, in some cases, a characteristic length. The base area is a face of the debris piece of interest, calculated assuming a given debris shape, and is simply a convenient area with which to work. The drag area factor works on the base area to cause some calculated drag area other than, or equal to, the base area. Originally, the base area was calculated in the same manner for all types of debris. In order to reflect observed basic differences in breakup which are dependent on debris material type, this has been changed so that the base area is calculated differently for different types of debris.

Also, the original MUDEMIMP code randomly assigned a drag area factor and a drag coefficient to each debris from separate input probability density distributions. However, a given drag coefficient is only applicable for a given shape moving with a given presented drag area at a given orientation. Thus, the drag area factor should be chosen to cause, as closely as possible, the presented drag area of the debris mass which corresponds with the debris drag coefficient. Since only the product of drag coefficient and drag area is important to the drag force (and thus debris trajectory), the product may be input into the code in place of separate drag area factor and drag coefficient inputs. The recommended code input for debris with three-dimensional breakup has changed in this manner. For two-dimensional breakup, a constant average drag coefficient is recommended, and the average drag area factor over all the debris areas is calculated by the code for each debris assuming a square disc shaped debris. These two basic modifications are discussed in more detail in Reference 2. Only the required inputs will be provided here.

A new input parameter, BKUP, has been introduced to distinguish between the possible types of breakup. The default value for BKUP is 2 for two-dimensional breakup for which the thickness of each debris is assumed constant and equal to the input wall thickness or masonry shell thickness ("L"). This value is appropriate for all components which are expected to breakup with some constant characteristic thickness. In these cases, no breakup is assumed to occur through the characteristic thickness. A value of BKUP equal to 3 is input if three-dimensional breakup is expected. Three-dimensional breakup causes fracture along all three planes of the debris, as with reinforced concrete walls or plaster walls.

The input for the drag coefficient distribution for three-dimensional breakup (such as reinforced concrete) is a uniform distribution varying between 1.0 and 2.0. For two-dimensional breakup (such as masonry or corrugated metal), a constant distribution with a value of 1.5 is input. The input parameter "L" for characteristic debris length is used to indicate wall thickness for metal or reinforced concrete walls and shell wall thickness for masonry walls. The use of the "k-factor" has been turned off by directing the user to input a constant distribution with a value of 1.0. The "k-factor" can still be used to change the effective drag area by using a distribution set to some value other than 1.0, but this is only recommended when making a single debris run or when all debris will translate with a specific orientation.

1.2.3 Debris Dispersion

A modified version (Version 1.1 or later) of the MUDEMIMP code (Reference 5) for Multiple Debris Missile Impact Simulation is used to determine the hazardous debris distance and debris dispersion for a building. The results of the component breakup and debris characteristics prediction are used to create input for the MUDEMIMP code. Originally written by Louis Huang at the Naval Civil Engineering Laboratory (NCEL), this code uses a probabilistic approach to include variations and uncertainties of launch/flight characteristics of each individual debris missile from an explosion. It uses the Monte-Carlo random sampling technique to select a set of launch/flight parameters for each debris piece. It then calculates the trajectory, impact range, and terminal kinetic energy of each piece based on the selected initial conditions. In addition to an output file containing all input and output parameters for every debris missile simulated, the code also outputs either a histogram of the accumulated number of hazardous debris as a function of impact range or a file containing these debris density data, which can easily be imported to a spreadsheet for plotting a histogram. Hazardous debris are defined as those debris with impact kinetic energies exceeding a critical energy input by the user, e.g. 58 ft-lbs. Significant modifications to the original code which were made during this program are discussed in detail in Reference 2.

General input and output information is discussed in this section, but detailed input descriptions can be found in Reference 5. Descriptions of the changes in input from the code version described in Reference 5 are summarized in Section 2.1, step 8. Five main launch/flight parameters are required to run the code: debris mass, initial velocity, initial trajectory angle, drag coefficient, and drag area factor. The actual input to the code is in the form of probability distributions which describe the possible range of values for each major parameter. Parameters for each individual debris piece are chosen by the code randomly selecting from the probability distributions. The probability density functions recommended for the five main launch/flight parameters for concrete and masonry debris are shown below. The inputs for debris dispersion predictions of components constructed with other materials have been discussed in the previous sections.

- exponential -- debris mass
- normal -- initial veloc
- normal -- initial trajectory angle
- uniform or constant (depending on component material) -- drag coefficient
- constant -- drag area factor (due to changes in code discussed below)

These distributions are recommended based on extensive statistical sampling of the data from concrete and masonry tests conducted for this program. The drag coefficient for each individual debris simulation remains constant and is not allowed to vary with Mach number because, for most materials, the model is limited to considering debris which fly in the subsonic speed region where drag coefficient is not significantly affected by debris velocity (velocities less than 1000 ft/sec). Above 1000 ft/sec, the drag coefficient increases with increasing velocity. Therefore, it is always conservative to consider the drag coefficient to be independent of debris velocity. Other input includes initial height of debris and characteristic length. All debris are assumed to be launched from a single point. Refer to Section 2.1 and References 2 and 5 for a more complete description of the input.

1.2.4 Debris Tumble After Impact (Roll and Ricochet)

If debris thrown from an explosion impacts the ground at a shallow angle, it will ricochet or roll after impact. Predicting the first impact location as the final resting place is very inaccurate and unconservative. Logic to calculate debris ricochet and roll distances from curve fits to test data is incorporated in Version 1.1 of the MUDEMIMP code. The test data include tests on masonry and concrete walls from both severe close-in loading and severe quasistatic loading. The curve fits are discussed in detail in Reference 2. According to the roll and ricochet logic built into the code, the total debris throw distance is the sum of the distance to the first impact and the roll distance. The roll distance is calculated from the debris angle and velocity at first impact. Debris angle is only considered to the extent that debris with an impact angle less than 55 degrees from the horizontal are assumed to roll, whereas those debris impacting at higher angles are assumed not to roll. The debris impact velocity is used with curve fits from the DOE/DoD test data (Reference 2) and other data (References 6 and 7) to calculate the roll distance. According to the curve fits, the roll distance increases with the impact velocity to the 1.9 power for reinforced concrete, and it increases bilinearly with impact velocity for masonry. The curve fit which was developed in Reference 7 was used to describe roll distance as a function of impact velocity for concrete debris because a slight scale dependence was noted. The BKUP parameter, which is described in Section 1.2.2.3, causes the model to differentiate between concrete roll (roll of debris with three-dimensional breakup) and masonry roll (roll of debris with two-dimensional breakup).

No curve fits of debris roll were developed for lightweight wall debris or beams. There are not enough data available to develop curve fits. Initial attempts to predict measured debris distances for tests of these materials, assuming no roll, significantly underpredicted the measured distances. Predictions were also made assuming roll similar to that of masonry. These predictions compared conservatively to measured debris distances. Therefore, dispersion of all debris which exhibits two-dimensional breakup, i.e. breakup which does not include any fracture through the beam thickness, should be predicted assuming debris roll according to the curve fit developed for masonry. Breakup of light walls and beams is assumed to be two-dimensional breakup.

Logic for ricochet (modelled after the ricochet logic in the FRAGHAZ code discussed in Reference 8) is also incorporated in Version 1.1 of the MUDEMIMP code. However, the DOE/DoD tests indicated the phenomenon for building debris was a combination of roll and ricochet of debris, with an emphasis on the rolling effect. Use of the ricochet logic from FRAGHAZ did not cause predicted maximum debris distances which were in good agreement with measured values from test wall debris. Although the ricochet option is still in the MUDEMIMP code, the empirical roll option is recommended for concrete and masonry debris. Section 2.1 shows how to access either option.

1.2.5 Hazardous Debris Density

The manner in which debris density is calculated by the MUDEMIMP code has been modified in Version 1.1 to allow a more realistic horizontal spread of debris and to calculate debris density based on the cumulative number of debris which have passed through an a[illegible] The use of a cumulative number of debris recognizes the hazard caused to vertical targets by low angle debris. The MUDEMIMP code calculates the minimum siting distance for protection from hazardous debris as that distance at which there are no more than one hazardous debris (having a kinetic energy of at least 58 ft-lb, or any critical energy defined by the user in the input file) per 600 square feet.

The MUDEMIMP code previously determined density by assuming square collection bins with the dimensions of 24.5 feet, the square root of 600 square feet. No consideration was given to the observed change in horizontal deviation off the normal to the responding component with change in distance downrange from the component. Also, the densities were not previously cumulative, i.e. debris passing through the vertical area above the bins were not included in the density calculations. Therefore, the previous version of the MUDEMIMP code was conservative in its calculation of bin area, but unconservative in its calculation of number of debris within a grid, compared with the new version to be used in the debris dispersion model. To obtain a more realistic estimate of debris density, several modifications were made to Version 1.1 of MUDEMIMP.

The first step in the logic that MUDEMIMP Version 1.1 now uses to calculate debris density is to divide the distance downrange from the center of the building into segments using a specified segment length. All debris landing within each segment length are assumed to land in the same grid. The debris density is the cumulative number of debris landing within, or passing through, each segment divided by the grid area associated with the segment.

The specified segment length is defined by a new input parameter, GRIDL. This parameter is equal to the destroyed width of the component (Equation 30). For close-in loading of concrete and for all masonry loading, the destroyed width, GRIDL, is calculated assuming that all the debris is ejected from a circular disk out of the wall centered opposite the charge. GRIDL is equal to the diameter of this disk. For far-range loading of concrete, GRIDL is equal to the wall width since debris may be ejected from any portion of the wall for this type of loading. The grid area associated with each segment length is a trapezoidal area where the altitude of the trapezoid is equal to the segment length (GRIDL), and the sides of the trapezoid perpendicular to the altitude extend between the angles along the ground radiating outward from either side of the total destroyed width of the building wall. This is illustrated in Figure 1. Thus, the widths of these sides of the trapezoid are defined assuming debris is thrown out from the edges of the destroyed component width (GRIDL) at a maximum five degree horizontal spread angle. The five degree angle was established based on the horizontal spread of debris observed in Swedish tests of reinforced concrete rectangular buildings exposed to internal detonations (Reference 9) and on the measured horizontal spread of debris in the tests conducted for DOE/DoD. This is discussed in more detail in Reference 2.

The area of each trapezoidal bin is divided into the cumulative number of debris passing through, or landing within, the segment length to determine the debris density at the midpoint of the segment length. Only critical debris are totaled. The calculated density is then converted by the code to a number of debris per 600 square feet.

1.3 Model Constraints

The predictive model provides conservative estimates of maximum and hazardous building debris distances which can be expected following an accidental explosion. The model is based largely on curve-fits to data collected from small scale tests and full scale tests. Therefore, the confidence level in the model is highest for conditions similar to the testing conditions. Some extrapolation beyond these regions seems necessary in order to provide a flexible model. Data other than that in Reference 2 are very limited and do not consider all the broad range of building materials and possible loading conditions present at DOE and DoD facilities. The most probable or most common conditions were considered. Practical limitations such as available debris collection area and charge weight limitations did not allow some parameters to be tested throughout all the realms that may be of importance to debris throw from explosives operations buildings.

In order to create a model with an acceptable degree of flexibility (and thus a reasonably wide range of applicability) from the data which were collected, data gaps are filled by using conservative analytical procedures or by limited extrapolation of curve-fits to data. Use of the model outside the limits of the test data but within the limits called out in this section has been carefully analyzed. It is judged that use of the model in this region will produce conservative results. This analysis is discussed in Reference 2. Extrapolation of curve-fits is only used where no acceptable analytical approach or test data are available.

Since test data for dispersion of building debris for situations outside the limits of the model are extremely limited, extrapolation of the model to analyze situations outside the limits discussed here must be approved on a case-by-case basis. Such extrapolation should be done with considerable care and engineering judgment. Specific limitations on the use of the model are summarized in the remainder of this section.

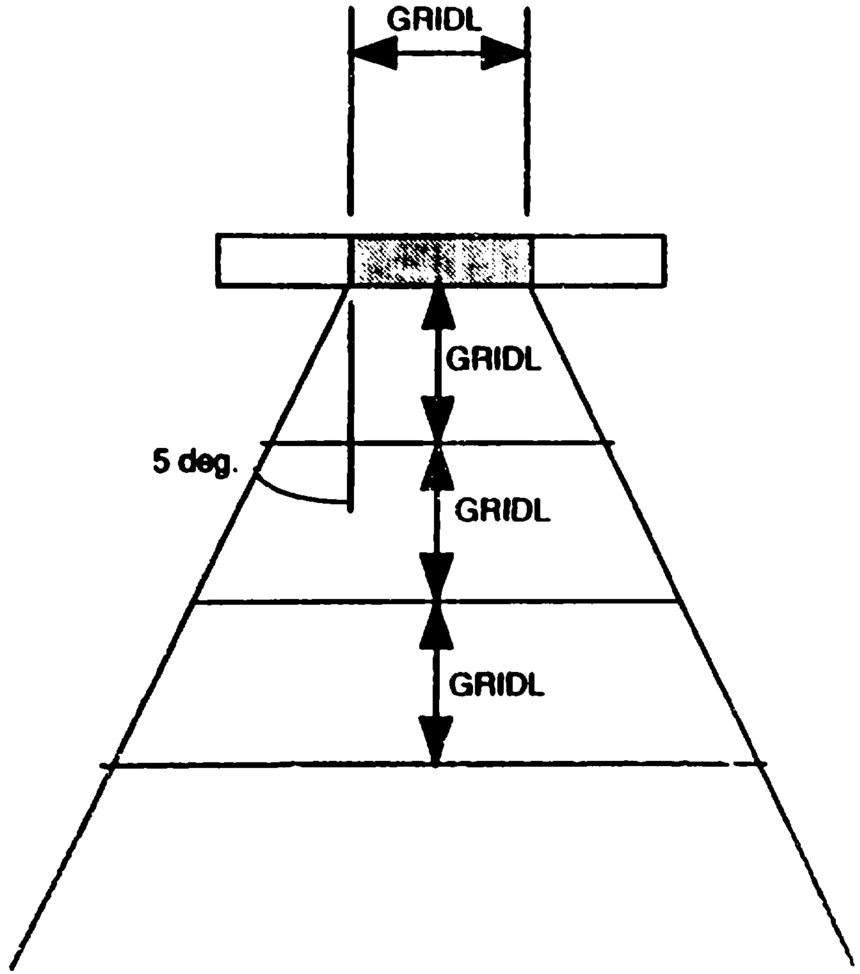

Figure 1. Grid Areas Used by MUDEMIMP Code to Calculate Debris Density

1.3.1 Charge Weight Limitations

The model is limited to use for charge weights equal to, or less than, 250 pounds TNT equivalent. Supporting tests used only bare spherical explosive charges so the methods described in this paper for determining loads on a surface apply to these type charges. However, the thrust of the model is the prediction of hazardous debris distance. The procedure for determining this distance, beginning with the calculation of maximum debris velocity, can be applied to loads predicted by methods other than those described herein. The user should predict loads using the best method known for a particular explosive configuration and should thoroughly document any assumptions made regarding charge characteristics and location. One should note that the use of the SHOCK code in determining loads automatically means a spherical charge is being assumed. If an equivalent spherical charge is known or assumed to be the case, one can follow the load prediction procedure presented in steps 1 through 4.B of Section 2.1. If a different procedure is known for a different charge configuration (e.g., cylindrical or multiple charges), the user would use the loads determined using that procedure and begin at step 4.C in Section 2.1 to obtain the hazardous debris distance. Some information on loading prediction techniques for other charge configurations is provided in Reference 3.

As mentioned, the model may be used for buildings with multiple charges (totaling no more than 250 pounds) if the combined impulse on a component from all the charges which may sympathetically detonate is conservatively calculated on a case-by-case basis. The reduction factor (discussed in Section 1.2.2.1) which may be applied to the maximum velocity of concrete and masonry debris shall be taken as 1.0 (no reduction) for any charge shape other than spherical and for cases where multiple charges are sympathetically detonated. Since use of the SHOCK code implies a spherical explosive configuration, the reduction factor should be used if this code is used to predict loads for concrete or masonry debris.

The largest scaled charge weight used in the DOE/DoD test series scaled to 200 pounds TNT at full scale. The charge used was Composition C4 explosive for which the TNT equivalency factor has been measured. This measured factor was used to determine the amount of C4 to use to model 200 pounds. Because DOE uses a common factor of 1.3 to convert any high explosive to a TNT equivalent weight, the amount modeled by the largest charge weight tested corresponds to 240 pounds. Extrapolating this value to 250 pounds is reasonable considering the loading differences expected for a 10 pound difference in charge weight for this magnitude of explosive amount. Therefore, this charge weight is taken as the limit for the model.

1.3.2 Scaled Charge Standoff Limitations

The model is limited to use for scaled charge standoffs greater than 0.5 $ft/lb^{1/3}$. This is the smallest scaled standoff used in the test series. Also the standoff is limited to at least 1.5 feet. This is the smallest full scale standoff used in the test series and it is less than the minimum required standoff in most buildings. The minimum standoff limitation is primarily intended to prevent the model from use for situations involving small charges nearly in contact with the wall.

1.3.3 Debris Material Limitations

Only building debris dispersion may be calculated with this model. Dispersion of primary debris, such as that from bomb casings, and secondary debris, such as unconstrained or constrained objects located close to the charge, must be calculated using other methods such as those in Reference 3, and must be approved on a case-by-case basis. Calculation of door trajectories, for example, is not covered by this model, but Reference 3 or 4 can be used to determine the throw distance for such items. Roll, similar to the roll of masonry debris, should probably be included in the calculation of the total stopping distance of doors. This recommendation is based on results of some highly confined tests conducted as part of the program described in Section 3.0. These tests were conducted in a box consisting of three nonresponding walls, a nonresponding roof, and a reinforced concrete test wall. The concrete wall, which would be similar to a steel door in a reinforced concrete structure, moved out from the box as one large unit and did exhibit roll characteristics. The descriptions of these tests in Reference 2 would be useful to someone analyzing door trajectories.

Building components constructed of reinforced concrete, unreinforced masonry, lightweight metal panels, and cement asbestos panels may be analyzed using the model. Components of other materials, such as reinforced masonry, may be analyzed if debris throw is judged to be conservatively estimated by debris throw from an equivalent component constructed of the materials listed above. All factors important to debris dispersions, such as mass per unit area and strength, must be conservatively estimated for the component of interest by the equivalent component.

Buildings with no lightweight components which quickly relieve the quasistatic buildup in the building as they fail must be analyzed with the model using caution. Specifically, such buildings where the vent panel (the component with the least weight per unit area) is a reinforced concrete wall are not addressed in this paper. Reference 2 contains further discussion on analyzing this type of structure. Scaled test data for such situations show that the model calculation procedures do not account for some phenomena which may occur for this case. In the tests it was observed that as the large quasistatic load vented through narrow hinge lines in the reinforced concrete test walls, the air flow imparted additional velocity to debris near the hinge lines causing much higher velocities than those predicted by the model. However, the number of debris traveling at these higher velocities is generally low relative to the total number of debris produced so they probably will not set the hazardous debris distance. In cases of high confinement such as those discussed here, the user should keep in mind that the default criteria apply when constraints of this model are exceeded.

1.3.4 Maximum Debris Velocity Limitations

The general use of the model is limited to consideration of debris at velocities less than 1000 ft/sec. At velocities greater than 1000 ft/sec, drag forces on the debris significantly change from those assumed by the model. The exception to this limitation is debris resulting from the breakup of corrugated metal walls or roofs. Two tests were conducted on corrugated metal walls as part of the DOE/DoD test program (Reference 2). The test data are obviously limited, but velocities higher than 1000 ft/sec were measured for these tests, both of which used a TNT equivalent charge amount of 25 pounds in half scale (at different standoff distances from the wall). Based on these limited data and the conservative method used by the model to predict throw distances for this type of debris, the mode! can be used for higher velocities for corrugated metal components. The full scale charge limit of 250 pounds alone should be used for this type of component without applying an additional velocity limitation.

2.0 Guidelines for Using the Model

Three computer codes -- SHOCK, FRANG, and MUDEMIMP -- are required to use the model. The versions of SHOCK and FRANG used during model development are the versions obtained from NCEL and are designed to run on a personal computer (PC). Version 1.0 of SHOCK, with the last NCEL modification dated 10/21/87, or later, and the Waterways Experiment Station (WES) version of SHOCK are acceptable. The final release of Version 1.0 of FRANG, dated 8/29/88, or a later version may be used. The MUDEMIMP code obtained from Louis Huang when he worked at NCEL was designed to run on a mainframe VAX computer. For much of the model refinement task, MUDEMIMP was run on a VAX 780 so that the appropriate graphics routines (from a proprietary graphics package) could be utilized. A PC version of MUDEMIMP, Version 1.1, has been created which will provide the same output except it has no graphics capability. The PC version does, however, create an extra output file containing the data necessary to create a final density histogram of number of hazardous debris as a function of distance in a form convenient for importing into a spreadsheet.

2.1 Step-by-Step Approach

Step-by-step guidelines for using the model to determine proper siting distance for a building follow. More complete descriptions of the analysis used to establish these steps and the tests used to collect the backup data can be found in Reference 2.

1. Define the threat. Describe all the structural components which comprise the building. Define the explosive charge amount and location. Generally, for siting purposes, the charge location should be a plausible worst case location which would cause the worst case debris formation. Some trial and error may be necessary to define this location. All assumptions and known information regarding charge characteristics and location should be documented (see Section 1.3.1).

2. <u>Determine vent areas and descriptions</u>. Define both covered and open vent areas and the weight per unit area of the covered areas.

3. <u>Calculate the impulse load on each component</u>. Establish the loading condition of the component being analyzed. Two types of loading are possible: close-in loading and far-range loading. The methods of calculating the load for each case are summarized here.

A. Shock Impulse (i_s)

1) Brittle materials with significant strength (reinforced concrete)

a) Close-in (0.5 ft/lb$^{1/3}$ < R/W$^{1/3}$ ≤ 1.0 ft/lb$^{1/3}$)

where R = charge standoff distance (ft)

W = equivalent TNT charge weight (lb)

SHOCK code -- impulse and duration at point on component opposite the charge location

b) Far-range (R/W$^{1/3}$ > 1.0 ft/lb$^{1/3}$)

if R ≥ L/4 ft,
SHOCK code -- average impulse over full component (L = component width in ft)

if R < L/4 ft,
average impulse over local component area of 2R x 2R directly opposite charge (L = component width in ft)

2) Brittle materials without significant strength (unreinforced masonry, plaster, built-up roof)

Both loading realms -- SHOCK code impulse and duration at point opposite the charge

if 2.5 ft/lb$^{1/3}$ < R/W$^{1/3}$ < 5 ft/lb$^{1/3*}$, multiply SHOCK impulse by factor I_f to account for observed unconservativeness of SHOCK code in this loading realm, where

$$I_f = 0.4\,(R/W^{1/3}) \qquad (1)$$

if $R/W^{1/3} \geq 5$ ft/lb$^{1/3}$*, multiply SHOCK impulse by 2.0 to account for observed underestimation of SHOCK code in this loading realm

*Note: Do not use when calculating shock loads for use in the FRANG code. These checks on scaled standoff and the use of multiplication factors on the impulse only apply to point shock loads, not average loads.

3) Ductile materials (steel beams, corrugated metal panels)

Both loading realms -- SHOCK code average impulse over the beam or metal panel with the highest loading

B. Quasistatic Impulse (i_q)

The FRANG code is used to predict i_q. Version 1.0 (released 8/29/88) of FRANG does not consider combined covered vent areas. Only one covered vent area can be input. The method presented here of running the code twice to determine a conservative estimate of quasistatic impulse is due to the limitations of this version of FRANG.

1) Brittle material with significant strength (reinforced concrete) and brittle material without significant strength (unreinforced masonry, plaster, built-up roof)

a) Close-in ($R/W^{1/3} \leq 1.0$ ft/lb$^{1/3}$)

aa) Run FRANG with vent panel = vent component; the vent component is the building component with the least weight per unit area; use appropriate FRANG parameters for vent component

ab) Run FRANG with vent panel = local component area opposite the charge; input appropriate FRANG parameters for local area; local area dimensions are 2R x 2R (modified, if necessary, for height of the charge off the ground) and area is centered on the component directly opposite the charge

ac) Use lesser of total quasistatic impulse from aa) or quasistatic impulse at critical vent time, indicated on FRANG output as "AMAX", obtained using procedure in ab)

b) Far-range ($R/W^{1/3} > 1.0$ ft/lb$^{1/3}$)

Run FRANG with vent panel = vent component as in aa) above; use total gas impulse unless vent component is the component of interest; if vent component is component of interest, use impulse at "AMAX"*

* If "AMAX" does not appear in FRANG output, use the total quasistatic impulse

2) Ductile material except steel beams (corrugated metal panels)

For both loading realms, calculate impulse in the same manner as 1b) above for brittle materials, far-range loading realm. If the ductile member is a door with a weight per unit area which differs from the vent component weight per unit area by a factor of 2 or less, use the gas impulse at "AMAX". The door will not receive the full gas load in this case. If the door weight per unit area is greater than twice the vent component weight per unit area, use the total gas impulse.

3) Steel beams

Do not include any quasistatic impulse because the material supported by the beams will vent much more quickly. The full quasistatic impulse would not be applied to the beams. In many instances, the beams will not even break away from the structure. The trajectories for beams or similar ductile members should still be determined in case these members do break free and become missiles.

$i_q = 0.0$ psi-sec

4. <u>Calculate the maximum debris velocity expected.</u>

The basic form of the velocity calculation is

$$(1/R_f)(i/m) \tag{2}$$

where i is the total impulse, m is the mass per unit area of the component, and R_f is the appropriate reduction factor. The equations and guidelines for calculating R_f are summarized below. This factor should be used whenever the SHOCK code has been used to obtain the shock impulse, i_s.

Reinforced Concrete:

$$R' = (i_s/m)(\text{duration})^{0.67}/(f'_c)^{0.5} \qquad (3)$$

$$R_f = [2.8 - 21.4(R')] \quad \text{for } R' < 0.084 \ (\text{inch}^2/\text{sec}^{0.33}\text{lb}^{0.5})^*$$
$$R_f = 1.0 \quad \text{for } R' \geq 0.084 \qquad (4)$$

Unreinforced Masonry:

$$R' = (i_s/m)(\text{duration}) \qquad (5)$$

$$R_f = [1.7 - 1.3(R')] \quad \text{for } R' < 0.54 \ (\text{inch})^*$$
$$R_f = 1.0 \quad \text{for } R' \geq 0.54 \qquad (6)$$

*Note: These dimensions can be attained for (i/m) in inch/sec, duration in seconds, and the concrete compressive strength, f'_c, in psi.

The specific guidelines for determining velocity follow.

A. Calculate relevant shock impulse (i'_s)
(Determine whether reduction factor, R_f, should be used.)

1) Brittle materials with significant strength (reinforced concrete)

a) Close-in ($R/W^{1/3} \leq 1.0$ ft/lb$^{1/3}$)

Use impulse and duration from SHOCK and component mass per unit area and compressive strength to calculate reduction factor (R_f) from curve-fit for reinforced concrete, close-in load

$$i'_s = i_s / R_f \qquad (7)$$

b) Far-range ($R/W^{1/3} > 1.0$ ft/lb$^{1/3}$)

$$i'_s = i_s \qquad (8)$$

2) Brittle materials without significant strength (unreinforced masonry, plaster, built-up roof)

For both close-in and far-range loads, use impulse and duration from SHOCK and component minimum mass per unit area to calculate the reduction factor (R_f) from curve-fit for unreinforced masonry. The minimum component mass per unit area is explained in Part C of this section. If the brittle material is not unreinforced masonry, use $R_f = 1.0$.

$$i'_s = i_s / R_f \tag{9}$$

3) Ductile materials (steel beams, corrugated metal panels)

For both close-in and far-range loads

$$i'_s = i_s \tag{10}$$

B. Calculate the total relevant impulse (i_T)

$$i_T = i_q + i'_s \tag{11}$$

C. Calculate the maximum debris velocity (V_{max}). Use consistent units.

1) Solid components (except steel beams)

$$V_{max} = i_T / m \tag{12}$$

where m = component mass per unit area

2) Hollow components

$$V_{max} = i_T / m' \tag{13}$$

where m' = minimum mass per unit area

m' is the mass per unit area of the sum of solid portions through the thickness of the hollow block where this value is a minimum.

3) Steel beams

This velocity calculation is taken from Reference 10. Figure 2 provides illustrations of four commonly used structural steel members. Consult this figure for further descriptions of the parameters used in Equation (14).

$$V^*_{max} = [T/\rho]^{1/2}[-0.41 + 0.41(i_T L^{-0.3} b)/((\rho T)^{1/2} A)] \tag{14}$$

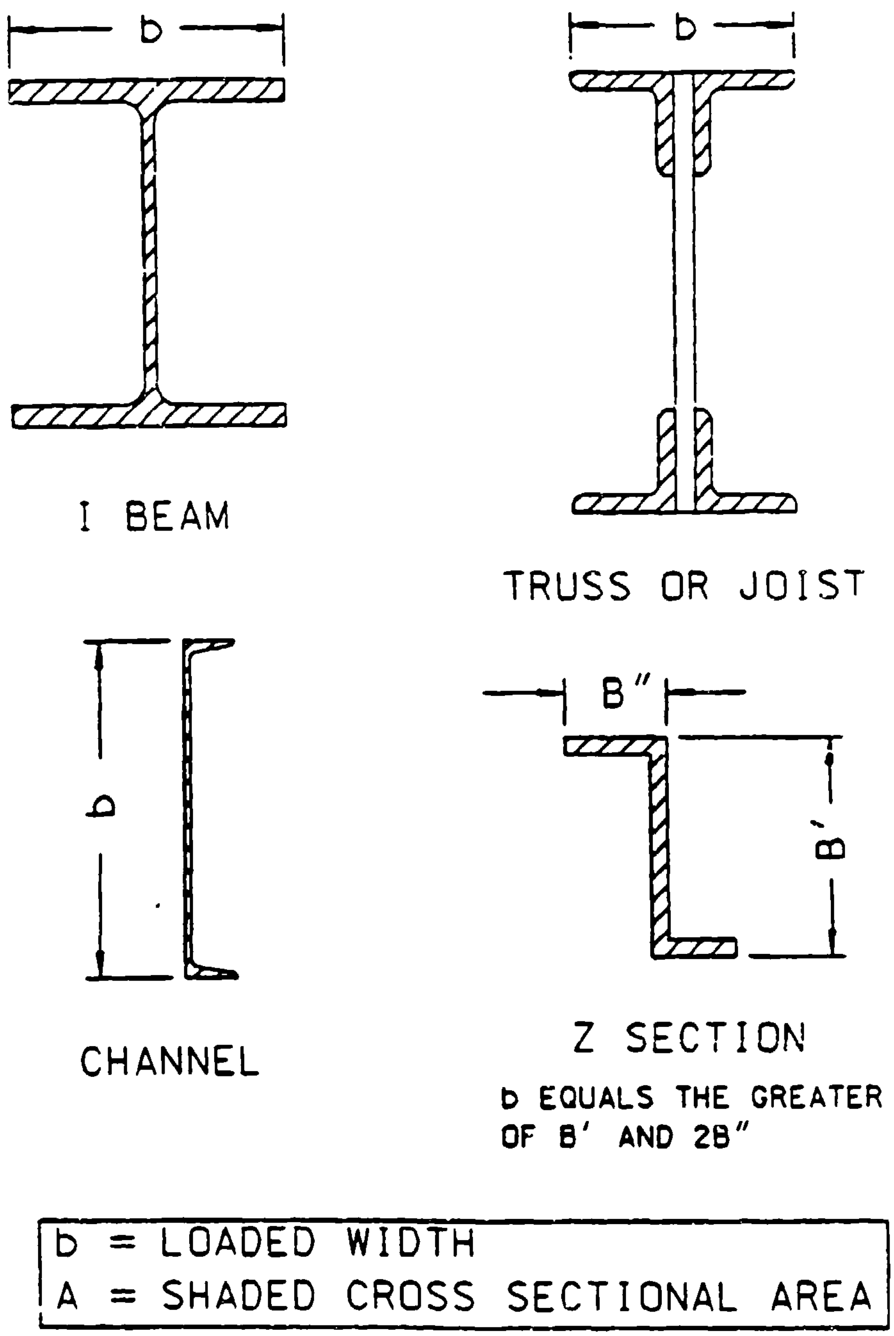

Figure 2. Commonly Used Structural Steel Members

where	V_{max}	= beam velocity (in/sec)
	i_T	= total relevant impulse (psi-sec)
	T	= beam material toughness (lb-in/in^3)
		= 12000 lb-in/in^3 for mild steel (toughness is the area under the material stress-strain curve at failure)
	L	= beam length (inch)
	b	= largest beam cross-sectional dimension which could be blast loaded (inch)
	L′	= (2 L)/b
	A	= beam cross-sectional area in the plane perpendicular to the long axis (inch^2)
	w	= weight per unit length of beam (lb/in)
	g	= gravity constant (in/sec^2)
	ρ	= w/Ag (lb-sec^2/inch^4)

for $(i_T L'^{0.3} b)/((\rho T)^{1/2} A) > 9.0$

$$V_{max} = (i_T b) / (\rho A) \tag{15}$$

* A calculated zero or negative velocity indicates the beam does not fail and, therefore, no further consideration of the beam is required.

4) Doors

The distance traveled by a door can be determined using methods such as those described in Reference 3. The door should not be added into the debris densities for the other building components to establish hazardous distances. The distance traveled by the door should be considered on its own since the door is such a major fragment. In most cases, one would want to design a shield or barricade to stop the door from traveling very far.

D. Calculate the average velocity and velocity standard deviation.

The average debris velocity and debris velocity standard deviation used to define the normal velocity distribution are calculated directly from the maximum debris velocity.

Average velocity: $$V_{avg} = (0.6)\,(V_{max}) \tag{16}$$

Velocity standard deviation: $$V_{std} = (0.14)\,(V_{max}) \tag{17}$$

5. <u>Calculate the average debris weight</u>. The parameter used as input for the MUDEMIMP code is actually a weight and not a mass. However, the MUDEMIMP code refers to this parameter as a mass. The code converts the weight to a mass internally. The empirically based equations for average debris weight, m_{avg}, are in the form shown below for concrete and masonry debris. For steel beams, the debris is considered to be the entire beam with a mass equal to the beam mass. For lightweight metal panels, the mass is assumed to be uniformly distributed between the values m_{max} and m_{min} shown below.

$$m_{avg} = M' \text{ (volume) (density)} \tag{18}$$

where M′ is a factor based on fits to data.

The specific equations for reinforced concrete and masonry walls are shown below. If using English units, m_{avg}, m, m_{min}, and m_{max} should be in pounds.

Concrete:

$$m_{avg} = 0.10 \text{ [(rebar spacing)}^2 \text{ (cover thickness) (density)]} \tag{19}$$

Masonry:

$$m_{avg} = (M') \text{ [(shell face thickness)}^3 \text{ (density)]} \tag{20}$$

where M′ is related to maximum debris velocity, V_{max}

$$\begin{aligned} M' &= 98.5 - 0.74(V_{max}) \quad \text{for } V_{max} < 120 \text{ (ft/sec)} \\ M' &= 10 \quad \text{for } V_{max} \geq 120 \end{aligned} \tag{21}$$

Steel beams:

$$m = \text{total beam mass} \tag{22}$$

Lightweight metal panels:

$$m_{max} = \text{total panel mass} \tag{23}$$
$$m_{min} = \text{one-quarter of the total panel mass} \tag{24}$$

6. <u>Determine the effective destroyed weight of the component (wall or roof)</u>. The MUDEMIMP code requires the input of the total destroyed mass of the component. Again, this parameter is actually input as a weight and then converted to mass within the code. The main use of this input by the code is to help define the input mass

distribution and establish the adjustment factor to get the appropriate number of debris (as adjusted from the 5000 simulations). The effective destroyed mass is determined as follows:

$$\text{Total effective destroyed mass} = T' \text{ (total component weight)} \qquad (25)$$

where the component is the wall or roof being analyzed and T' is calculated as follows. If using English units the total effective destroyed mass is in pounds.

Reinforced concrete with close-in loading ($R/W^{1/3} \leq 1.0$ ft/lb$^{1/3}$):

$$\begin{array}{ll} T' = 1.0 & V_s > 353 \text{ ft/sec} \\ T' = 0.00308(V_s) - 0.089 & 45 < V_s \leq 353 \text{ ft/sec} \\ T' = 0.05 & V_s < 45 \text{ ft/sec} \end{array} \qquad (26)$$

where $V_s = i'_s/m$ or portion of V_{max} due to shock impulse

Reinforced concrete with far-range loading ($R/W^{1/3} > 1.0$ ft/lb$^{1/3}$):

$$\begin{array}{ll} T' = 0.1 & V_{max} \geq 45 \text{ ft/sec} \\ T' = 0.05 & V_{max} < 45 \text{ ft/sec} \end{array} \qquad (27)$$

Unreinforced masonry and plaster:

$$\begin{array}{ll} T' = 1.0 & V_{max} \geq 190 \text{ ft/sec} \\ T' = 0.00655(V_{max}) - 0.245 & 45 < V_{max} < 190 \text{ ft/sec} \\ T' = 0.05 & V_{max} < 45 \text{ ft/sec} \end{array} \qquad (28)$$

Lightweight metal panels and steel beams:

$$T' = 1.0 \qquad (29)$$

7. <u>Calculate destroyed width ("GRIDL" in MUDEMIMP) of the component</u>.

Assume a circular destroyed area equal to the total effective destroyed mass divided by the component weight per unit area. If English units are used, the width should be in feet.

$$GRIDL = \sqrt{((4/\pi)(\textit{total effective destroyed mass})/(\textit{weight per unit area}))} \qquad (30)$$

8. Run MUDEMIMP to determine hazardous debris distance. The main input parameters are summarized below.

Parameter	Density Function	Limits
Mass	Exponential for concrete and masonry Uniform for lightweight metal panels Constant for beams	m_{avg} m_{min}, m_{max} total beam mass
Total Mass	No distribution	total effective destroyed mass
Initial Velocity	Normal Constant for beams	mean = $V_{avg} = 0.6(V_{max})$ sd* = $V_{sd} = 0.14(V_{max})$ V_{max}
Initial Trajectory Angle	Normal Constant for beams	mean = the normal to the surface measured relative to the horizontal sd* = 1.3 or 10 degrees angle = the normal to the surface measured relative to the horizontal
Drag Area Factor	Constant	1.0
Drag Coefficient (3-dimensional breakup) Drag Coefficient (2-dimensional breakup) Drag Coefficient (beams)	Uniform Constant Constant	1.0, 2.0 1.5 1.8

* sd = standard deviation

sd = 1.3 degrees	(a) close-in loading of concrete, masonry, and plaster components (b) far-range loading of masonry and plaster components (c) far-range loading of concrete components not restrained by the roof
sd = 10 degrees	(a) all loading of corrugated metal components

(b) far-range loading of concrete walls restrained at the roof
(c) all roofs

The general form of a MUDEMIMP input file is included here. For further descriptions of those variables unchanged in Version 1.1, consult Reference 5.

```
NE,INE
NMCV,TOTMASS,INTRPFX,RKE,ID,RANDM
Title
FT      LBS     SEC     FT-LBS
MASS    EXPONENT    m_avg
VELOCITY NORMAL     V_avg    V_std
ANGLE   NORMAL      mean     std
COF     UNIFORM     1.0      2.0
KFACTOR CONSTANT    1.0
END
1  150.
7  3.0
8  1.0
10 1.0
12 3.0
19 -15.0
```

The parameters and in the first three lines are:

NE	=	number of elements to be run (use 1)
INE	=	number of repeated executions (use 1 because confidence in the statistical distributions is taken care of using a value of 5000 for NMCV)
NMCV	=	number of random Monte-Carlo simulations (use 5000)
TOTMASS	=	total effective destroyed mass
INTRPFX	=	type of curve smoothing to be used in histogram plots (does not apply to PC Version 1.1 of MUDEMIMP; use 0)
RKE	=	critical kinetic energy (for current criteria, use 58)
ID	=	"OUTPUT" if trajectory output is desired
RANDM	=	initial random seed to be used in generating parameter distributions (use 14555568.0)
Title	=	user's input for the title of a run

Other key input parameters in addition to the probability density functions and those parameters described above include material density, launch height, wall thickness, type of breakup (two or three dimensional), and grid length for use in determining hazardous debris density (calculated in Step 7). The other parameters all have default values assigned to them within the code. If the user wishes to change the default value of any parameter, he or she must include the change in the input file. This is accomplished by calling out the positions of the parameter array (NL) to be changed and indicating the values to be assigned to those parameters which need to be different from the default values (see the example problems in the Appendix). Parameters not to be changed need not be entered. A negative sign must be placed in front of the value for the last parameter input to indicate to the code that input is complete. A summary of the parameters in the NL array, including parameter descriptions and default values in bold print in parentheses, is included here. The code allows input of English or metric units. The units are indicated on the fourth line of the input file. If units of feet/pounds/seconds are not used, the indicated default values will not apply, and all parameters listed here will need to be input with appropriate values.

1	D	= density of debris material (**490. lbs/ft^3**)
2	N	= number of angular intervals for the upward portion of the trajectory (**10**)
3	CO	= ambient sound speed (**1116.45 ft/sec**)
4	DO	= ambient density (**0.076474 lbs/ft^3**)
5	G	= acceleration of gravity (**32.174 ft/sec^2**)
6	ES	= energy conservation factor (**32.174 ft/sec^2**)
7	BKUP	= breakup factor (=2 for 2-dimensional; =3 for 3-dimensional) (**2**)
8	IRIC	= ricochet factor (=0 for first impact distance only, =1 for including empirical roll, =2 for including FRAGHAZ ricochet logic) (**1**)
9	B	= fragment shape factor (**0.**)
10	L	= wall thickness or shell thickness for masonry (**0. ft**)
11	X	= initial horizontal coordinate for fragment (**0. ft**)
12	Y	= initial vertical coordinate for fragment (**0. ft**)
13	X9	= maximum x-coordinate allowed for trajectory (**0. ft**) (the default value indicates no maximum x-coordinate will be considered)
14	Y9	= minimum y-coordinate allowed for trajectory (**0. ft**)
15	J	= print control variable (**0**)
16	I	= angular increment for the upward portion of the trajectory (**0 degrees**)
17	I2	= angular increment for the downward portion of the trajectory (**0 degrees**)
18	N2	= number of angular intervals for the downward portion of the trajectory (**0**)
19	GRIDL	= effective destroyed width equal to one length of simulated collection bin (**24.5 ft**)

Normally, for the use of the MUDEMIMP code in the prediction model, the user would only need to input changes for the parameters D, Y, L, BKUP, and GRIDL.

The Y parameter is the average launch height for the wall debris with the highest velocities. It is recommended that this be set equal to the height of the charge for close-in loading and the mid-height of the wall for far-range loading of concrete, masonry, and other brittle materials. The beam height and mid-height of the most highly loaded panel should be used for ductile debris. For roofs, the Y parameter is the height of the midpoint of the roof.

As stated above, the wall thickness, or the thickness of one shell for masonry, should be input for L. For steel beams, L should be determined based on the expected presented area:

$$L = \text{mass} / ((\text{density})\ (\text{area}))$$

Three-dimensional breakup (BKUP = 3) applies when no typical dimension characterizes debris thickness. This is recommended for concrete and plaster wall breakup. Two-dimensional breakup (BKUP = 2) applies when a dimension, such as the wall thickness or masonry shell thickness, characterizes typical debris thickness. This is recommended for materials such as metal panel walls, built-up roofs, steel beams, and masonry breakup.

The exact form of an input file for MUDEMIMP is illustrated in the example calculations in the Appendix and in Reference 2.

9. <u>Obtain pertinent information from the program output files</u>.

The model is run for each component of a building. The two key output files from the PC version of MUDEMIMP are MIMP.HIS and MIMP.OUT. The MIMP.HIS file contains two columns of data which can be plotted to provide a histogram of number of hazardous debris per 600 square feet as a function of distance. The first column contains the midpoint of each grid established by the program based on the user's input of the destroyed width of a surface, GRIDL. The second column contains the number of hazardous debris per 600 square feet found in each grid. Although the current PC version of this code does not produce a plot, the data is in a format which can easily be imported to one of several common spreadsheet programs to obtain a histogram. This file also indicates the hazardous debris distance and the maximum impact distance of any debris for a particular run.

The number of hazardous debris in a certain direction will be the graphical sum of the number of hazardous debris from the wall components facing that direction and half of the roof hazardous debris. The graphical sum is obtained using the histograms for the wall and the roof. Half of the roof debris are used since potentially half of these debris could contribute to the hazard in a particular direction.

The MIMP.OUT file contains the code selected values of debris characteristics for each debris simulated in the run. This file can be used to examine further details about the debris landing farthest from the source, the debris with the highest initial angles, or other specific debris.

2.2 Interpretation of Results

The debris siting criteria in DoD 6055.9-STD (Reference 1) require siting of inhabited buildings at distances at which there are no more than one hazardous fragment per 600 square feet. A hazardous fragment is defined as one having a kinetic energy of 58 ft-lb or greater. The manner in which this hazardous fragment density is determined has varied from one hazards analysis to another, especially in the calculation of fragment densities involving building debris. A standard procedure for calculating building debris density is needed to determine compliance with the safety criteria. The method now included within the MUDEMIMP code reflects debris spread expected from actual accidents based on debris data collected as part of the DOE/DoD funded test program and on Swedish test data from internal detonations within reinforced concrete buildings (Reference 9). This method is discussed in more detail in Section 1.2.5.

The output of the MUDEMIMP code is either a histogram showing number of hazardous debris per 600 square feet as a function of distance or a file containing two columns indicating (1) distance to centers of defined code collection bins and (2) number of debris landing in each bin. This file can then be imported to a spreadsheet program to create a histogram from the data. Thus, after working through an analysis of a building, the final result for each building component will indicate not only the maximum distance at which there is no more than one fragment per 600 square feet, but also the distribution of hazardous debris expected following an accidental internal detonation. In addition, the furthest distance traveled by any simulated debris piece is indicated in the output file.

Empirical relationships are used throughout the model to determine input for the dispersion code. These curve fits are based on reinforced concrete and masonry data measured during the test programs described in References 2 and 7. A best fit through the data was always used. Thus, the final predicted debris distances were not always conservative for each test. To establish a 95% confidence level in the conservatism of the final predicted distance, based on these test data, a safety factor of 1.3 should be applied to the predicted hazardous debris distance for concrete and masonry components. This factor accounts for scatter between the test data and the curve fits, and the expected variation between accidents. It differs from the practice of applying a factor of 1.3 to the net explosive weight to convert it to an equivalent TNT weight and then applying a safety factor of 1.2 before making any loading or debris calculations. The first factor of 1.3 (or the actual TNT equivalent factor) should still be applied to the net explosive weight; however, no other multiplication factor should be used on the charge weight.

The final safety factor of 1.3 is based on a statistical analysis of the ratio of predicted maximum debris distance to measured maximum debris distance for 22 reinforced concrete and unreinforced masonry tests. Of these 22 tests, 8 maximum distances were underpredicted (resulted in a ratio less than 1.0). The initial significance of the value of 1.3 is that this number is the reciprocal of the lowest ratio of predicted to measured maximum distance, i.e. the most unconservative case out of the 8 referenced tests is underpredicted by 30%. The safety factor of 1.3 applied to each of the 8 data points was then statistically examined. The ratios of predicted distance (including the applied safety factor) to measured maximum distance were fit to a Weibull distribution to determine the certainty with which the model will produce conservative results. Confidence levels of 90% and 95% were tested for reliability in the model. A confidence level of 95% was selected based on the results of this analysis. If distances predicted by the model are multiplied by a safety factor of 1.3, one can be 95% confident that only 11.6% of the predicted maximum distance values would be less than the corresponding actual distance values (i.e., ratio less than 1.0). It is important to note that the safety factor of 1.3 should only be applied to distances predicted for concrete and masonry debris. No safety factor should be used for the ductile material debris covered by the model. Comparisons of predicted distance to measured distance for these materials indicates the predictions are already conservative (Reference 2).

The maximum and hazardous debris distances (including the safety factor) for each building component are then examined to determine the siting distance required in each direction around the building. The roof debris is generally distributed equally in four directions, and the model can distribute debris in two dimensions only. The debris for a given direction should therefore include debris from the component facing that direction and half of the roof debris. The hazardous distance in any direction is determined by summing the number of debris from the component facing that direction (including all debris from that component) and half of the roof debris, and using this number to calculate debris density. Although the hazardous debris distance in each direction will govern the siting distance, the maximum debris distances are informative and can be important if more stringent siting criteria are enacted for any reason. One exception to the use of the hazardous debris distance in governing the siting distance is the analysis of a building containing one or more components composed of steel beams. The maximum debris distance predicted when making single debris runs with the MUDEMIMP code (all probability density distributions set as constant) for steel beam debris should be compared to the hazardous debris distance (based on hazardous debris density) predicted for other debris in a given direction. The greater distance of hazardous debris distance or maximum steel beam debris distance will set the siting distance in each direction.

3.0 Supporting Test Program

An extensive test program was conducted to obtain data on debris characteristics and wall failure patterns for the wall types most commonly found in DOE facilities. The test program included full, half, and quarter scale tests of reinforced concrete, unreinforced masonry, and lightweight metal walls. Wall thickness, reinforcement details, and concrete strength were varied in the concrete wall tests. The masonry wall tests included tests of various geometries of clay tile walls and full and quarter scale concrete masonry unit (CMU) walls. The testing was highly concentrated on concrete and masonry wall breakup, but two corrugated metal walls and one metal stud wall were also tested. Although the metal walls were all tested in a fully vented (open air) configuration, three different loading conditions were used for the concrete and masonry walls: fully vented, partially vented, or closed. Three separate test fixtures were used to allow testing of different scales and loading conditions. The explosive charges used varied in amount from 0.2 lb to 25 lb TNT equivalent. Due to the different scales of tests conducted, the full scale range of charge weights varied from 12 lb to 200 lb. Further details of these tests and complete data summaries can be obtained from Reference 2.

3.1 Data Collection

Much of the data collected in the test program were debris characteristics from quarter scale reinforced concrete or unreinforced masonry walls subjected to either close-in loads (scaled standoff distances less than 1.0 ft/lb$^{1/3}$) or a large quasistatic load. These two general loading conditions will cause the worst case debris distances. Other loading conditions, such as far-range loading without large quasistatic loading, will cause considerably less building component damage. Since the data for these other loading scenarios were either very limited or nonexistent, the use of conservative methods to estimate debris dispersion in the model is acceptable for these cases.

The two main methods of debris data collection consisted of data measured directly from a test bed divided into a large grid and data measured off high-speed films of the event. Each of the test fixtures was set up at the end of a large test bed. Following a test, debris were collected within designated squares of a grid designed to cover the debris spread from each test. Average mass, number of debris coming to rest at a certain distance, maximum debris distance, hazardous debris distance, and horizontal spread of debris out from the test component were all determined directly from the collection of debris in the test bed. Other data including wall response characteristics, debris velocity, vertical debris trajectory angle, and debris roll and ricochet after impact were measured using high-speed films of each test. Vertical background grids placed on the edge of the test bed were used as a reference in making the measurements. Debris velocities, angles, and sizes were sampled off the high-speed film at selected intervals to obtain appropriate sample sizes on which to perform statistical goodness of fit tests. These tests were used to establish the probability density distributions needed as input to the MUDEMIMP code.

In addition to the component breakup and debris data collected, internal and external blast measurements were made for the confined tests conducted. One of the test fixtures was a concrete-filled, steel box with two open ends in which different wall components could be placed to model various venting conditions. The box fixture was instrumented with four reflected blast pressure gauges and three quasistatic pressure gauges for internal load measurements. These loads were measured so they could be compared to the loads predicted using the SHOCK and FRANG computer codes.

3.2 Model Refinement from Test Data

The test data from the DOE/DoD program were analyzed to refine the parameters in the predictive model which were being predicted with an inadequate level of confidence. These parameters were mainly the building component breakup parameters, including debris initial velocity, initial trajectory angle, and mass. The data were also used to devise a method to account for debris roll and ricochet after first impact and to verify loading prediction techniques. These factors are vital to the model because debris dispersion is heavily dependent on the debris initial flight conditions during component breakup (particularly initial velocity) and on the distance debris roll after first impacting the ground. Roll accounts for a large portion of the total distance traveled by the debris from walls not laterally restrained at the top, which is a typical condition for the types of buildings studied in the DOE/DoD program. The resulting refined prediction methods for component breakup parameters consist primarily of empirical relationships between loading parameters and component mass and strength to measured breakup parameters. Debris roll was found to be proportional to the velocity at the first impact and is also affected by the initial angle at which a piece leaves a wall or roof. Thus, debris velocity, average debris mass, total effective destroyed mass for a component, and debris roll are all based directly on test data resulting from the program described in Reference 2.

Building component breakup is described in the model in terms of probability density distributions of debris mass, velocity, trajectory angle, drag coefficient, and drag area. The debris velocities and angles sampled off the high-speed film and the masses of all the collected debris were statistically analyzed to determine the distributions of these parameters which best fit the data. The resulting distributions were normal distributions for debris initial velocity and angle and an exponential distribution for debris mass. In addition, scatter plots of debris velocity, angle, and size show that the measured debris initial launch conditions are not strongly correlated. This observation is in agreement with the logic of the Monte-Carlo simulation procedure in the MUDEMIMP code which randomly assigns initial velocity, mass, and trajectory angle to each debris piece from the input probability density distributions.

4.0 Effect of Model on Building Siting Criteria

A brief overview of the hazardous debris dispersion prediction model has been presented in this technical paper, with an emphasis on how to use the model. It is flexible in that several different construction types can be analyzed using the model. Test data have been used as extensively as possible to verify or establish code input or calculation procedures. The intent has been to make the model as accurate as possible without requiring the use of highly sophisticated procedures to determine the input and run the model.

Minimum separation distances for protection from debris hazards are not changed by this paper. The requirement that the number of hazardous fragments at IBD be no greater than one remains in effect. This paper describes an approved, safety conservative method for predicting the distance where the hazardous fragment criteria are satisfied. Application of the model in this paper will often permit siting distance reductions from the broad-ranged criteria (670 or 1250 feet) now in Reference 1. However, in some cases predicted hazardous debris distances will even exceed the default distance criteria of Reference 1. In these cases, and because the model in this paper is considered safety conservative, the default criteria may be used.

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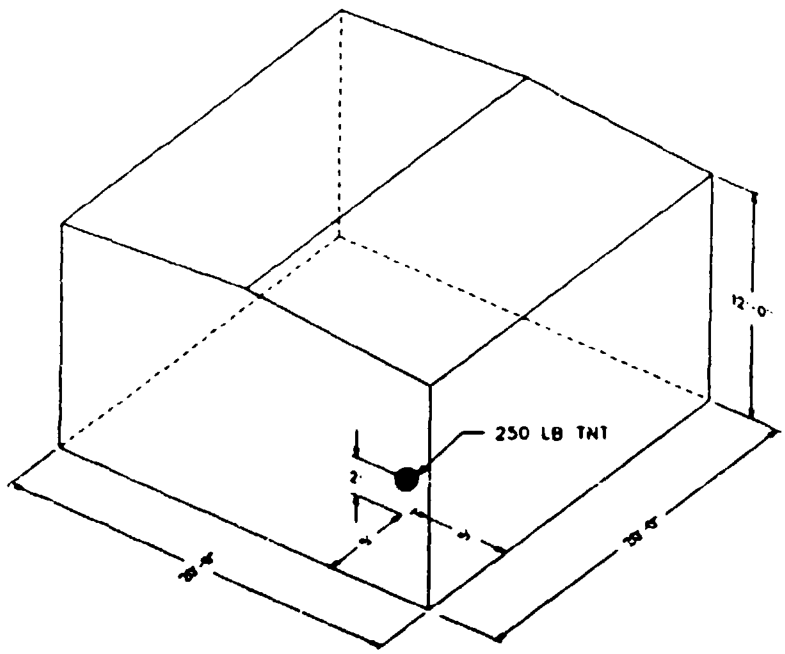
Appendix: Example Calculations

Example Problem No. 1

Step 1: Define the threat.

The building has four reinforced concrete walls (12 inches thick) and a sloped Cemesto® roof. The roof has a slope of one inch per foot (or a 5° slope). It consists of open web steel joists supporting Cemesto® panels spaced at 4 feet on center. The Cemesto® panel thickness is 1 9/16 inches. No door is included in this example. See Example Problem No. 2 for door calculations.



A bare spherical charge equivalent to 250 lb TNT is assumed. It is located 5 feet from the front wall, 5 feet from the left sidewall, and 2 feet from the floor. (This is an arbitrarily chosen location. The user needs to select the worst case location for each surface analyzed. Some guidelines for making this selection are included in Example Problem No. 3.)

Step 2: Determine the vent areas and descriptions.

No open vent areas.

One covered vent area -- the roof

covered vent area = (20)(20) = 400 ft^2

weight per unit area of Cemesto® roof = 4.7 lb/ft^2
(no snow load is assumed on the roof for this example)

vent perimeter = 4(20) = 80 ft

Step 3: Calculate the impulse load on each component.

Step 3A: Determine the shock impulse on each component.

Surface 1	12 ft x 20 ft reinforced concrete front wall
Surface 2	12 ft x 20 ft reinforced concrete wall closest to charge
Surface 3	12 ft x 20 ft reinforced concrete back wall
Surface 4	12 ft x 20 ft reinforced concrete wall furthest from charge
Surface 5	20 ft x 20 ft Cemesto® roof
Surface 6	steel joists

Surface 1: 12 ft x 20 ft reinforced concrete wall

Wall is a brittle material with significant strength

$R/W^{1/3} = 5/(250)^{1/3} = 0.79\ ft/lb^{1/3}$

Since 0.5 < 0.79 < 1.0, it is a close-in load. Use the SHOCK code to get the impulse and duration at a point opposite the charge.

W = 250 lb

Distance to blast surface = 5 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 5 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Reduced surface calculation for point = (5,2)

Shock impulse i_s for Surface 1 = 4.0 psi-sec

duration = 0.00068 sec

Surface 2: 12 ft x 20 ft reinforced concrete wall, 5 ft from charge

Wall is a brittle material with significant strength

$R/W^{1/3} = 5/(250)^{1/3} = 0.79\ ft/lb^{1/3}$

Since 0.5 < 0.79 < 1.0, it is a close-in load. Use the SHOCK code to get the impulse and duration at a point opposite the charge.

W = 250 lb

Distance to blast surface = 5 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 15 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Reduced surface calculation for point = (15,2)

Shock impulse i_s for Surface 2 = <u>4.0 psi-sec</u>

duration = <u>0.00068 sec</u>

<u>Surface 3</u>: 12 ft x 20 ft reinforced concrete back wall

Wall is a brittle material with significant strength

$R/W^{1/3} = 15/(250)^{1/3} = 2.4\ ft/lb^{1/3}$

Since 2.4 > 1.0, it is a far-range load.

Component width = L = 20 ft, L/4 = 5 ft

R = 15 ft

Since R ≥ L/4, use the SHOCK code to calculate the average impulse over the full wall area.

W = 250 lb

Distance to blast surface = 15 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 15 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load

Shock impulse i_s for Surface 3 = <u>1.2 psi-sec</u>

duration = <u>0.00373 sec</u>

Surface 4: 12 ft x 20 ft reinforced concrete right side wall

Wall is a brittle material with significant strength

$R/W^{1/3} = 15/(250)^{1/3} = 2.4$ ft/lb$^{1/3}$

Since 2.4 > 1.0, it is a far-range load.

Component width = L = 20 ft, L/4 = 5 ft

R = 15 ft

Since R ≥ L/4, use the SHOCK code to calculate the average impulse over the full wall area.

W = 250 lb

Distance to blast surface = 15 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 5 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load

Shock impulse i_s for Surface 4 = 1.2 psi-sec

duration = 0.00373 sec

Surface 5: 20 ft x 20 ft Cemesto® roof

Roof is a brittle material without significant strength

Use the SHOCK code to get the impulse and duration at a point opposite the charge.

$R/W^{1/3} = 10/(250)^{1/3} = 1.6$ ft/lb$^{1/3}$

Since 1.6 < 2.5, no multiplication factor will be applied to the im[illegible] lated at a point with the SHOCK code.

W = 250 lb

Distance to blast surface = 10 ft

Width of blast surface = 20 ft

Height of blast surface = 20 ft

Horizontal distance from reflecting surface 2 = 5 ft (front wall)

Vertical distance from reflecting surface 1 = 15 ft (left sidewall)

4 reflecting surfaces

Reduced surface calculation for point = (5,15)

Shock impulse i_s for Surface 5 = 1.85 psi-sec

duration = 0.00128 sec

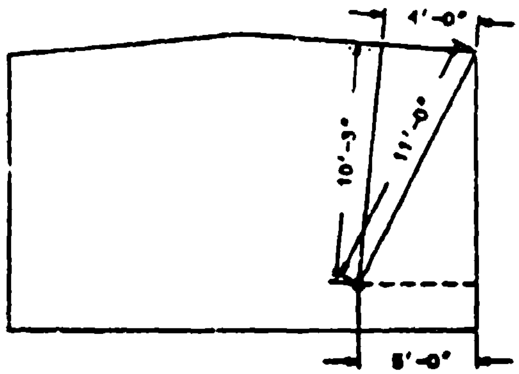
Surface 6: Steel joist in roof

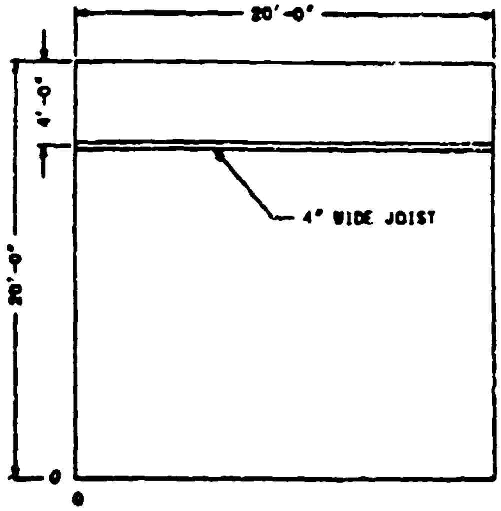
Joist is a ductile material (like a steel beam)

Use the SHOCK code to get the average impulse over the loaded width of the joist with the highest loading. Based on the assumed joist dimensions, this width is 4 inches.

W = 250 lb

Distance to blast surface = 10.3 ft to closest joist





ROOF AS LOADED SURFACE

Width of blast surface = 20 ft

Height of blast surface = 20 ft

Horizontal distance from reflecting surface 2 = 5 ft (front wall)

Vertical distance from reflecting surface 1 = 15 ft (left sidewall)

4 reflecting surfaces

Average load on reduced surface of joist

Coordinates of upper left corner = (0,16.17)

Coordinates of lower right corner = (20,15.83)

Shock impulse i_s for Surface 6 = 1.4 psi-sec

duration = 0.00175 sec

Step 3B: Determine the quasistatic impulse on each component.

The quasistatic impulse to be included in the load of each component may vary since this example building has brittle material with significant strength and brittle material without significant strength.

Surfaces 1 and 2: 12 ft x 20 ft reinforced concrete front wall and side wall closest to the charge

Brittle material with significant strength

Close-in load ($R/W^{1/3} = 0.79 < 1.0$)

Make 2 FRANG runs (see Step 3B 1) a) aa) - ac)).

FRANG Run No. 1

Vent panel = vent component = roof

W = 250 lb

Volume = (20)(20)(12) = 4800 ft^3
(conservatively ignore volume under sloped roof)

Covered vent area = 400 ft^2

Vent perimeter = 80 ft

Surface weight/area = 4.7 lb/ft^2

Shock impulse on panel = 0.35 psi-sec = 350 psi-msec
(SHOCK was rerun to get average load on full roof area.)

Uncovered vent area = 0

Recessed depth of panel = 0

Total quasistatic impulse = 1.6 psi-sec

FRANG Run No. 2

Vent panel = local component area on Surface 1 or 2 opposite the charge

W = 250 lb

Volume = (20)(20)(12) = 4800 ft^3
(conservatively ignore volume under sloped roof)

Covered vent area = 2R x (R + 2) = 2(5)(7) = 70 ft^2
(have to adjust recommended 2R x 2R area due to charge height of 2 ft)

Vent perimeter = 2(2)(5) + 2(7) = 34 ft

Surface weight/area = (150 lb/ft^3)(1 ft) = 150 lb/ft^2

Shock impulse on local area:

Run SHOCK with reduced area option for Surface 1

Coordinates of upper left corner = (0,7)

Coordinates of lower right corner = (10,0)

So shock impulse = 3179 psi-msec

Uncovered vent area = 0

Recessed depth of panel = 1 ft
The recessed depth of 1 ft is used here since the assumed locally failed portion of the wall must move through the thickness of the remaining portion of the wall before venting will occur.

Quasistatic impulse at critical vent time = 4.8 psi-sec

Use the lesser of quasistatic impulse from the two FRANG runs.

i_q = 1.6 psi-sec for Surfaces 1 and 2

Surfaces 3 and 4: 12 ft x 20 ft reinforced concrete back and side wall

Brittle material with significant strength

Far-range load ($R/W^{1/3} = 2.4 > 1.0$)

Run FRANG with vent panel = vent component and use the total quasistatic impulse. This is the same run as FRANG Run No. 1 for Surfaces 1 and 2, so i_q = 1.6 psi-sec for Surfaces 3 and 4.

Surface 5: 20 ft x 20 ft Cemesto® roof

Brittle material without significant strength

$R/W^{1/3} = 10/(250)^{1/3} = 1.6$ ft/lb$^{1/3} > 1.0$

This is a far-range load.

Run FRANG with vent panel = vent component and use the impulse at the critical vent time, indicated by AMAX on the output. The run is the same as FRANG Run No. 1 for Surfaces 1 and 2, but we need to use the impulse at AMAX, so

i_q = 1.2 psi-sec for Surface 5

Surface 6: Steel joist

This member is treated as a steel beam would be treated by the model.

i_q = 0.0 psi-sec

Step 4: Calculate the maximum debris velocity expected for each component.

Step 4A: Calculate the relevant shock impulse, i_s'

Surfaces 1 and 2: Reinforced concrete walls

Brittle material with significant strength

Close-in load $(R/W^{1/3} = 0.79 < 1.0)$

Calculate the reduction factor, R_f, from Equation (3)

$$R' = (i_s/m)\ (\text{duration})^{0.67} / (f_c')^{0.5}$$

where i_s = shock impulse

m = mass per unit area of component

f_c' = concrete compressive strength

So, $i_s = 4.0$ psi-sec

$m = (150\ \text{lb/ft}^3)(1\ \text{ft}) = 150\ \text{lb/ft}^2 = 1.04\ \text{lb/in}^2$

$f_c' = 4000$ psi

duration = 0.00068 sec

$i_s/m = [(4.0\ \text{psi-sec})(386.4\ \text{in/sec}^2)] / (1.04\ \text{lb/in}^2) = 1486\ \text{in/sec}$

$R' = (1486)(0.00068)^{0.67} / (4000)^{0.5} = 0.18\ \text{in}^2/\text{sec}^{0.33}\ \text{lb}^{0.5}$

Since $0.18 \geq 0.084$, $R_f = 1.0$

Essentially, the relevant shock impulse = shock impulse

$i_s' = i_s/R_f = 4.0/1.0 =$ 4.0 psi-sec

Surfaces 3 and 4: Reinforced concrete walls

Brittle material with significant strength

Far-range load $(R/W^{1/3} = 2.4 > 1.0)$

So, $i_s' = i_s =$ 1.2 psi-sec

Surface 5: Cemesto roof

Brittle material without significant strength, but it is not masonry.

So, $R_f = 1.0$

By Equation (9)

$i_s' = i_s/R_f = 1.85/1.0 =$ <u>1.85 psi-sec</u>

<u>Surface 6</u>: Steel joist

Ductile material

$i_s' = i_s =$ <u>1.4 psi-sec</u>

<u>Step 4B</u>: Calculate the total relevant impulse, i_T for each surface.

Use Equation (11)

$i_T = i_q + i'_s$

<u>Surfaces 1 and 2</u>: Reinforced concrete walls

$i_T = 1.6 + 4.0 =$ <u>5.6 psi-sec</u>

<u>Surfaces 3 and 4</u>: Reinforced concrete walls

$i_T = 1.6 + 1.2 =$ <u>2.8 psi-sec</u>

<u>Surface 5</u>: Cemesto® roof

$i_T = 1.2 + 1.85 =$ <u>3.05 psi-sec</u>

<u>Surface 6</u>: Steel joist

$i_T = 0.0 + 1.4 =$ <u>1.4 psi-sec</u>

<u>Step 4C</u>: Calculate the maximum debris velocity, V_{max}, for each surface.

<u>Surfaces 1 and 2</u>: Reinforced concrete walls

Solid components -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 5.6$ psi-sec

$m = 150\ lb/ft^2 = 1.04\ lb/in^2$

$V_{max} = [(5.6)(386.4)] / (1.04) = 2081$ in/sec = <u>173 ft/sec</u>

<u>Surfaces 3 and 4</u>: Reinforced concrete walls

Solid components -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 2.8$ psi-sec

$m = 150\ lb/ft^2 = 1.04\ lb/in^2$

$V_{max} = [(2.8)(386.4)] / (1.04) = 1040$ in/sec = <u>87 ft/sec</u>

<u>Surface 5</u>: Cemesto® roof

Solid component -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 3.05$ psi-sec

$m = 4.7\ lb/ft^2 = 0.033\ lb/in^2$

$V_{max} = [(3.05)(386.4)] / (0.033) = 35700$ in/sec = <u>2975 ft/sec</u>

<u>NOTE</u>: The maximum velocity for Cemesto® debris from the roof exceeds the model limit of 1000 ft/sec. The calculated velocity is probably very conservative since the Cemesto® will break apart under the shock loading and allow more vent perimeter than that accounted for by the FRANG code. This will probably result in a lower quasistatic load. The model can be reasonably used for velocities higher than 1000 ft/sec for metal panel debris because test data verify its use. However, no test data were collected for Cemesto® debris. We will proceed to obtain hazardous distance for the roof debris, but recognize we are beyond data verified results.

<u>Surface 6</u>: Steel joist

Use Equation (14) or (15) to calculate V_{max}, as for a steel beam.

Assume the steel joist is composed of double 2" x 2" x 1/4" angles along the top and bottom chord. Use the weight per unit length estimated as 2.5 times the weight per unit length for a double angle to account for the double angles at the top and bottom chord and the web members.

So i_T = 1.4 psi-sec

T = beam material toughness = 12,000 lb-in/in³ (assuming A36 steel)

L = beam length = 20 ft = 240 in

b	=	loaded width
	=	4 in (width of top double angle for the joist)
L'	=	$2\ L/b = 2\ (240)/4 = 120$ in
A	=	$2(1.88\ in^2) = 3.76\ in^2$ (from AISC Steel Manual)
w	=	6.38 lb/ft for a double angle so use $w = 2.5\ (6.38) = 15.95$ lb/ft $= 1.33$ lb/in
g	=	gravity constant = 386.4 in/sec^2
ρ	=	$w/Ag = 1.33/[(3.76)(386.4)] = 0.00092$ lb-sec^2/in^4

First check

$$(i_T L'^{0.3} b)/((\rho T)^{1/2} A)$$

$$= [(1.4)(120)^{0.3}(4)]/[[(.00092)(12000)]^{1/2}(3.76)]$$

$$= (23.5)/(12.5) = 1.9$$

Since $1.9 \leq 9.0$

$$V_{max} = [T/\rho]^{1/2}[-0.41 + 0.41\ (i_T L'^{0.3} b)/((\rho T)^{1/2} A)]$$

$$V_{max} = [12000/.00092]^{1/2}\ [-0.41 + 0.41\ (1.9)]$$

V_{max} = 1333 in/sec = <u>111 ft/sec</u>

<u>Step 4D:</u> Calculate the average velocity and velocity standard deviation for each surface. Use Equations (16) and (17).

<u>Surfaces 1 and 2</u>: Reinforced concrete walls

V_{max} = 173 ft/sec

V_{avg} = (0.6)(173) = 104 ft/sec

V_{std} = (0.14)(173) = 24 ft/sec

<u>Surfaces 3 and 4</u>: Reinforced concrete walls

V_{max} = 87 ft/sec

V_{avg} = 0.6(87) = 52 ft/sec

V_{std} = 0.14(87) = 12 ft/sec

Surface 5: Cemesto® roof

V_{max} = 2975 ft/sec
V_{avg} = 0.6(2975) = 1785 ft/sec
V_{std} = 0.14(2975) = 416 ft/sec

Surface 6: Steel joist

Only need V_{max} = 111 ft/sec

Step 5: Calculate the average debris weight for each component.

Surfaces 1 - 4: Reinforced concrete walls

Use Equation (19)

m_{avg} = 0.10 [(rebar spacing)^2(cover thickness)(density)]

Assume rebar spacing = 12 in = 1 ft
cover thickness = 2 in = 0.17 ft
density = 150 lb/ft^3

So m_{avg} = 0.10(1)^2(0.17)(150) = 2.6 lb

Surface 5: Cemesto® roof

Use Equation (20) for masonry with shell face thickness = thickness of panel

m_{avg} = (M′)[(shell face thickness)^3(density)]

Use thickness = 1 9/16" = 0.13 ft
density = (4.7 lb/ft^2)/0.13 ft = 36 lb/ft^3

Since V_{max} = 2975 ft/sec > 120 ft/sec, use

M′ = 10

So, m_{avg} = 10(0.13)^3(36) = 0.8 lb

Surface 6: Steel joist

Equation (22)

m = total joist mass = (15.95 lb/ft)(20 ft) = 319 lb

Step 6: Determine effective destroyed weight of each component.

Surfaces 1 and 2: Reinforced concrete walls with close-in loading

Use Equations (26)

$V_s = i'_s/m = (4.0 \text{ psi-sec})(386.4 \text{ in/sec}^2)/(1.04 \text{ lb/in}^2)$
$= 1486 \text{ in/sec} = 124 \text{ ft/sec}$

Since $45 < 124 < 353$

$T' = 0.00308(124) - 0.089 = 0.29$

So, by Equation (25)

Total effective destroyed mass = (0.29)(12)(20)(1)(150)
= 10,440 lb

Surfaces 3 and 4: Reinforced concrete walls with far-range loading

By Equation (27)

$V_{max} = 87 \text{ ft/sec} \geq 45 \text{ ft/sec}$

So, $T' = 0.1$

Using Equation (25)

Total effective destroyed mass = (0.1)(12)(20)(1)(150)
= 3600 lb

Surface 5: Cemesto® roof

Use Equation (28) for unreinforced masonry

$V_{max} = 2975 \text{ ft/sec} \geq 190 \text{ ft/sec}$

So, $T' = 1.0$

Total effective destroyed mass = (1.0)(20)(20)(0.13)(36)
= 1872 lb

Surface 6: Steel joist

Use Equation (29) for beams, $T' = 1.0$

So, Total effective destroyed mass = (1.0)(319) = 319 lb for one joist

Step 7: Calculate the destroyed width, GRIDL, of each component except the steel joists. Constant distributions are used for the joists so it is like running single trajectories for them. The bin width should equal the length of a joist.

Use Equation (30)

Surfaces 1 and 2: Reinforced concrete walls

GRIDL = $\sqrt{(4/\Pi)(10440)/(150)}$ = 9.4 ft

Surfaces 3 and 4: Reinforced concrete walls

GRIDL = $\sqrt{(4/\Pi)(3600)/(150)}$ = 5.5 ft

Surface 5: Cemesto® roof

GRIDL = $\sqrt{(4/\Pi)(1872)/(4.7)}$ = 22.5 but the total width of the roof is only 20 ft so use GRIDL - 20 ft

Surface 6: Steel joist

Use GRIDL = joist length = 20 ft

Step 8: Set up input files for MUDEMIMP and run the code for each component (or like components).

Copies of each input file are included here.

Surfaces 1 and 2: Reinforced concrete walls

```
1,1
5000,10440.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 1 -- SURFACES (1) AND (2)
FT        LBS       SEC       FT-LBS
MASS      EXPONENT        2.6
VELOCITY  NORMAL         104.        24.
ANGLE     NORMAL           0.        1.3
COF       UNIFORM         1.0        2.0
KFACTOR   CONSTANT        1.0
END
1     150.
7     3.0
8     1.0
10    1.0
12     2.0
19   -9.4
```

Maximum cumulative hazardous distance = 616 ft

Maximum range = 632 ft

Surfaces 3 and 4: Reinforced concrete walls

```
1,1
5000,3600.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 1 -- SURFACES (3) AND (4)
FT          LBS        SEC        FT-LBS
MASS        EXPONENT           2.6
VELOCITY    NORMAL            52.          12.
ANGLE       NORMAL             0.          1.3
COF         UNIFORM            1.0         2.0
KFACTOR     CONSTANT           1.0
END
1     150.
7     3.0
8     1.0
10    1.0
12     2.0
19   -5.5
```

Maximum cumulative hazardous distance = 190 ft

Maximum range = 195 ft

Surface 5: Cemesto® roof

```
1,1
5000,1872.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 1 -- SURFACE (5)
FT          LBS         SEC         FT-LBS
MASS        EXPONENT          0.8
VELOCITY    NORMAL         1785.           416.
ANGLE       NORMAL           85.           10.0
COF         CONSTANT          1.5
KFACTOR     CONSTANT          1.0
END
1      36.
7      2.0
8      1.0
10     0.13
12     12.0
19    -20.0
```

Maximum cumulative hazardous distance = 430 ft

Maximum range = 483 ft

Considering half the roof debris (file the same except total effective destroyed mass = 1872/2 = 936 lb), the maximum cumulative hazardous distance = 410 ft.

Maximum range = 483 ft

Surface 6: Steel joists in roof

```
1,1
1,319.,0,58.,'OUTPUT',145555568.0
EXAMPLE PROBLEM 1 -- SURFACE (6)
FT        LBS       SEC       FT-LBS
MASS      CONSTANT       319.
VELOCITY  CONSTANT       111.
ANGLE     CONSTANT        85.
COF       CONSTANT        1.8
KFACTOR   CONSTANT        1.0
END
1  490.
7  2.0
8  1.0
10 0.2
12 12.0
19 -20.0
```

A note on the selection of "L" (input item 10) for a steel joist (or beam, etc.): It is difficult to estimate what area will be presented in flight. We will try to account for an average area by taking an area as

$$A = 0.5 \text{ (width of double angle)(joist length)}$$

$$A = 0.5 \text{ (4 in)(ft/12 in)(20ft)} = 3.3 \text{ ft}^2$$

The code internally determines area as

$$A = \text{mass}/((\text{density})(L))$$

So, use $L = \text{mass}/\rho A = 319 \text{ lb}/[(490 \text{ lb/ft}^3)(3.3 \text{ ft}^2)] = 0.2 \text{ ft}$

Maximum distance = 62 ft

Step 9: Make siting recommendation based on results for each direction from the structure.

The wall facing that direction and half the roof debris should be considered in each direction. The steel joists (if they break away) will not be setting the debris hazard so they will not be included in the summations. The maximum distance traveled by a joist was 62 ft. Again, this example did not include a door. See Example Problem No. 2 for door calculations.

Surface 1 or 2:

The maximum range of any of the roof debris is 483 ft. Since the cumulative hazardous debris for either of these two surfaces is 616 ft, the hazardous debris distance in the direction of surface 1 or 2 is 616 ft. (Cumulative densities at distances less than 483 ft would increase, but past 483 ft they will not change.)

Applying the 1.3 safety factor for concrete or masonry debris, the siting distance is (616)(1.3) = 801 ft.

Surface 3 or 4:

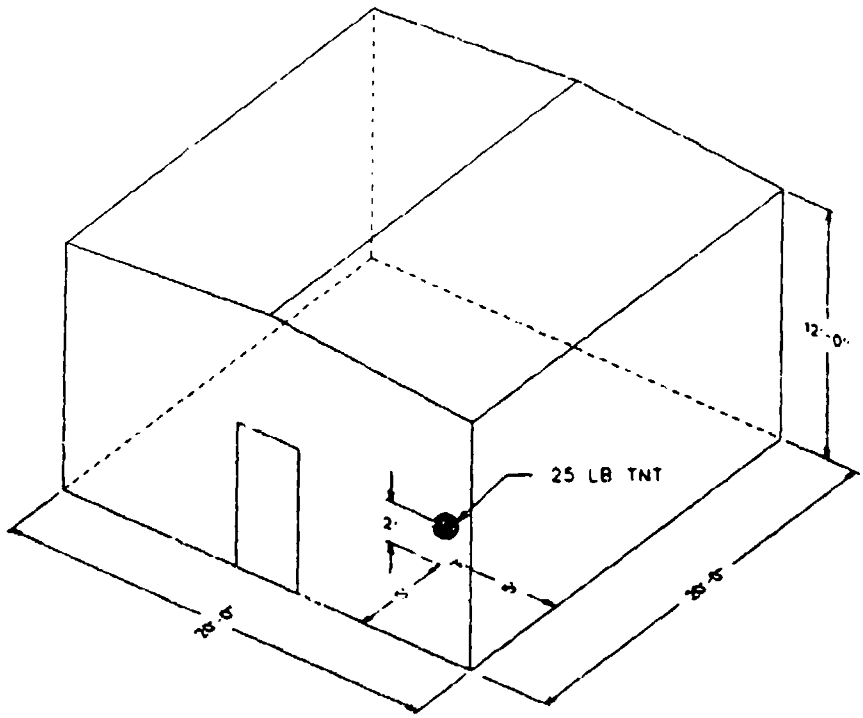
The maximum distance of wall debris in the direction out from surface 3 or 4 is 195 ft. The cumulative hazardous debris distance for half the roof debris is 410 ft. Although the cumulative densities for distances less than 195 ft will increase when roof and wall debris are considered, the hazardous debris distance in the direction of 3 or 4 is 410 ft.

(The 1.3 safety factor only applies to concrete or masonry debris distance and (195)(1.3) = 254 ft is still below 410 ft.)

Example Problem No. 2

Step 1: Define the threat.

The same building as in Example Problem No. 1 is used except a door is included. It has four reinforced concrete walls (12 inches thick) and a sloped Cemesto® roof. The roof has a slope of one inch per foot (or a 5° slope). It consists of open web steel joists supporting Cemesto® panels spaced at 4 feet on center. The Cemesto® panel thickness is 1 9/16 inches. A 3 feet by 7 feet hollow, 16 gauge steel door is included in Surface 1.



A bare spherical charge equivalent to 25 lb TNT is assumed. It is located 5 feet from the front wall, 5 feet from the left side wall, and 2 feet from the floor. (This is an arbitrarily chosen location. The user needs to select the worst case location for each surface analyzed. Some guidelines for making this selection are included in Example Problem No. 3.)

Step 2: Determine the vent areas and descriptions.

No open vent areas.

Two covered vent areas -- the roof and a door

The door weight/area is calculated as follows:

cover -- two 16 gauge steel plates (2 inch spacing)

$2(3\ ft)(7\ ft)(0.0598\ in)(ft/12\ in)(490\ lb/ft^3) = 102.6\ lb$

stiffeners

$6(36\ in)(4\ in)(0.0598\ in)(490\ lb/ft^3/(12\ in)^3) = 14.7\ lb$

total weight of door = 102.6 + 14.7 = 117.3 lb

weight/area = 117.3 / (3 ft)(7 ft) = 5.6 lb/ft^2

	Covered vent area (ft^2)	Weight/area (lb/ft^2)	Vent perimeter (ft)
Steel door	(3)(7)=21	5.6	20
Cemesto® roof	(20)(20)=400	4.7	80

Step 3: Calculate the impulse load on each component.

Step 3A: Determine the shock impulse on each component.

Surface 1	12 ft x 20 ft reinforced concrete front wall
Surface 2	12 ft x 20 ft reinforced concrete wall closest to charge
Surface 3	12 ft x 20 ft reinforced concrete back wall
Surface 4	12 ft x 20 ft reinforced concrete wall furthest from charge
Surface 5	20 ft x 20 ft Cemesto® roof
Surface 6	steel joists
Surface 7	hollow steel door

Surface 1: 12 ft x 20 ft reinforced concrete wall, L = 20 ft

Wall is a brittle material with significant strength

$R/W^{1/3} = 5/(25)^{1/3} = 1.7$ ft/lb$^{1/3}$, L/4 = 20/4 = 5 ft

Since 1.7 > 1.0, it is a far-range load.

Since L/4 ≥ 5, use the SHOCK code to get the average impulse over the full wall area.

W = 25 lb

Distance to blast surface = 5 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 5 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load

Shock impulse i_s for Surface 1 = 0.3 psi-sec

duration = 0.00137 sec

Surface 2: 12 ft x 20 ft reinforced concrete wall, 5 ft from charge, L = 20 ft

Wall is a brittle material with significant strength

$R/W^{1/3} = 5/(25)^{1/3} = 1.7$ ft/lb$^{1/3}$, L/4 = 20/4 = 5 ft

Since 1.7 > 1.0, it is a far-range load.

Since L/4 ≥ 5, use the SHOCK code to get the average impulse over the full wall area.

W = 25 lb

Distance to blast surface = 5 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 15 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load

Shock impulse i_s for Surface 2 = 0.3 psi-sec

duration = 0.00137 sec

Surface 3: 12 ft x 20 ft reinforced concrete back wall, L = 20 ft

Wall is a brittle material with significant strength

$R/W^{1/3} = 15/(25)^{1/3} = 5.1\ ft/lb^{1/3}$, $L/4 = 20/4 = 5$ ft

Since 5.1 > 1.0, it is a far-range load.

Since $R \geq L/4$, use the SHOCK code to calculate the average impulse over the full wall area.

W = 25 lb

Distance to blast surface = 15 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 15 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load

Shock impulse i_s for Surface 3 = 0.26 psi-sec

duration = 0.00661 sec

Surface 4: 12 ft x 20 ft reinforced concrete wall, 15 ft from charge, L = 20 ft

Wall is a brittle material with significant strength

$R/W^{1/3} = 15/(25)^{1/3} = 5.1\ ft/lb^{1/3}$, $L/4 = 20/4 = 5$ ft

Since 5.1 > 1.0, it is a far-range load.

Since $R \geq L/4$, use the SHOCK code to calculate the average impulse over the full wall area.

W = 25 lb

Distance to blast surface = 15 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 5 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load

Shock impulse i_s for Surface 4 = 0.26 psi-sec

duration = 0.00661 sec

Surface 5: 20 ft x 20 ft Cemesto® roof

Roof is a brittle material without significant strength

Use the SHOCK code to get the impulse and duration at a point opposite the charge.

$R/W^{1/3} = 10/(25)^{1/3} = 3.4\ ft/lb^{1/3}$

Since $2.5 < 3.4 < 5$, multiply the impulse calculated at a point with the SHOCK code by I_f where

$I_f = 0.4\ (R/W^{1/3}) = 0.4\ (3.4) = 1.36$ from Equation (1)

W = 25 lb

Distance to blast surface = 10 ft

Width of blast surface = 20 ft

Height of blast surface = 20 ft

Horizontal distance from reflecting surface 2 = 5 ft (front wall)

Vertical distance from reflecting surface 1 = 15 ft (left sidewall)

4 reflecting surfaces

Reduced surface calculation for point = (5,15)

Shock impulse i_s for Surface 5 = (0.329 psi-sec) (1.36)

= 0.45 psi-sec

duration = 0.002 sec

Surface 6: Steel joist in roof

Joist is a ductile material (like a steel beam)

Use the SHOCK code to get the average impulse over the loaded width of the joist with the highest loading. Based on the assumed joist dimensions, this width is 4 inches.

W = 25 lb

Distance to blast surface = 10.3 ft to closest joist

Width of blast surface = 20 ft

Height of blast surface = 20 ft

Horizontal distance from reflecting surface 2 = 5 ft (front wall)

Vertical distance from reflecting surface 1 = 15 ft (left sidewall)

4 reflecting surfaces

Average load on reduced surface of joist

Coordinates of upper left corner = (0,16.17)

Coordinates of lower right corner = (20,15.83)

Shock impulse i_s for Surface 6 = 0.26 psi-sec

duration = 0.003 sec

Surface 7: Hollow steel door, 3 ft x 7 ft, in Surface 1

Get the average load over the door using the SHOCK code for Surface 1 with a reduced area for the door.

W = 25 lb

Distance to blast surface = 5 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left sidewall = 5 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Average load on reduced surface of door

Coordinates of upper left corner = (8.5,7)

Coordinates of lower right corner = (11.5,0)

Shock impulse i_s for Surface 7 = 0.33 psi-sec

duration = 0.00119 sec

Step 3B: Determine the quasistatic impulse on each component.

The quasistatic impulse to be included in the load of each component may vary since this example building has brittle material with significant strength and brittle material without significant strength.

Surfaces 1 and 2: 12 ft x 20 ft reinforced concrete front wall and side wall closest to the charge

Brittle material with significant strength

Far-range load ($R/W^{1/3}$ = 1.7 > 1.0)

Run FRANG with the vent panel = vent component = roof. Since FRANG will only treat one covered vent area, choose the vent component which will cause the most venting. Both components actually allow venting, so choosing only one must be a conservative approach regardless of which surface is chosen. The simplest guidance is to choose the vent component with the largest blast loaded area. Another approach would be to consider both possible vent components with separate FRANG runs and choose the run with the <u>least</u> impulse. Since the roof area is much greater than the door area, the roof is chosen as the vent component to be used here.

W = 25 lb

Volume = (20)(20)(12) = 4800 ft^3
(conservatively ignore volume under sloped roof)

Covered vent area = 400 ft^2

Vent perimeter = 80 ft

Surface weight/area = 4.7 lb/ft^2

Shock impulse on panel = 0.22 psi-sec = 220 psi-msec
(SHOCK was rerun to get average load on full roof area. No multiplication factor was used since the load was averaged. The multiplication factor is only used on the impulse calculated with the SHOCK code at a point.)

Uncovered vent area = 0

Recessed depth of panel = 0

Total quasistatic impulse for Surfaces 1 and 2 = <u>0.59 psi-sec</u>

<u>Surfaces 3 and 4</u>: 12 ft x 20 ft reinforced concrete back and side wall

Brittle material with significant strength

Far-range load ($R/W^{1/3} = 5.1 > 1.0$)

Run FRANG with vent panel = vent component = roof and use the total quasistatic impulse. This is the same run as for Surfaces 1 and 2, so i_q = <u>0.59 psi-sec</u> for Surfaces 3 and 4.

<u>Surface 5</u>: 20 ft x 20 ft Cemesto® roof

Brittle material without significant strength

$R/W^{1/3} = 10/(25)^{1/3} = 3.4\ ft/lb^{1/3} > 1.0$

This is a far-range load.

Run FRANG with vent panel = vent component = roof and use the impulse at the critical vent time, indicated by AMAX on the output. The run is the same as for Surfaces 1 and 2, but we need to use the impulse at AMAX, so

i_q = <u>0.49 psi-sec</u> for Surface 5

Surface 6: Steel joist

This member is treated as a steel beam would be treated by the model.

i_q = 0.0 psi-sec

Surface 7: Hollow steel door, 3 ft x 7 ft

This is a ductile material. The weight/area from Step 2 is 5.6 lb/ft^2 which is 1.2 times the roof weight/area of 4.7 lb/ft^2.

Calculate the quasistatic impulse by running FRANG with the vent panel = vent component = roof. Since the door has much less area than the roof, and it is a light, hollow door without a large mass per unit area, it is safe to assume the door will be critically vented before the roof. Therefore, it is conservative to assume the door is exposed to the same amount of quasistatic impulse as the roof. A much less conservative, more accurate estimate of the door load can be made by using the ratios of roof to door mass per unit area and required movement to critical venting to choose a fraction of the quasistatic impulse prior to "AMAX" to apply to the door.

Using the same run as for Surfaces 1 and 2,

i_q = 0.49 psi-sec at "AMAX" for Surface 7.

Step 4: Calculate the maximum debris velocity expected for each component.

Step 4A: Calculate the relevant shock impulse, i_s'

Surfaces 1 and 2: Reinforced concrete walls

Brittle material with significant strength

Far-range load ($R/W^{1/3} = 1.7 > 1.0$)

So, $i_s' = i_s$ = 0.3 psi-sec from Equation (8)

Surfaces 3 and 4: Reinforced concrete walls

Brittle material with significant strength

Far-range load ($R/W^{1/3} = 5.1 > 1.0$)

So, $i_s' = i_s$ = 0.26 psi-sec from Equation (8)

Surface 5: Cemesto® roof

Brittle material without significant strength, but it is not masonry.

So , $R_f = 1.0$

By Equation (9)

$i_r' = i_r/R_f = 0.45/1.0 = \underline{0.45 \text{ psi-sec}}$

Surface 6: Steel joist

Ductile material

$i_r' = i_r = \underline{0.26 \text{ psi-sec}}$ from Equation (10)

Surface 7: Hollow steel door

Ductile material

$i_r' = i_r = \underline{0.33 \text{ psi-sec}}$ from Equation (10)

Step 4B: Calculate the total relevant impulse, i_T for each surface.

Use Equation (11)

$i_T = i_s + i'_r$

Surfaces 1 and 2: Reinforced concrete walls

$i_T = 0.59 + 0.3 = \underline{0.89 \text{ psi-sec}}$

Surfaces 3 and 4: Reinforced concrete walls

$i_T = 0.59 + 0.26 = \underline{0.85 \text{ psi-sec}}$

Surface 5: Cemesto® roof

$i_T = 0.49 + 0.45 = \underline{0.94 \text{ psi-sec}}$

Surface 6: Steel joist

$i_T = 0.0 + 0.26 = \underline{0.26 \text{ psi-sec}}$

Surface 7: Hollow steel door

$i_T = 0.49 + 0.33 = \underline{0.82 \text{ psi-sec}}$

Step 4C: Calculate the maximum debris velocity, V_{max}, for each surface.

Surfaces 1 and 2: Reinforced concrete walls

Solid components -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 0.89$ psi-sec

$m = 150 \text{ lb/ft}^2 = 1.04 \text{ lb/in}^2$

$V_{max} = [(0.89)(386.4)] / (1.04) = 331 \text{ in/sec} = \underline{28 \text{ ft/sec}}$

Surfaces 3 and 4: Reinforced concrete walls

Solid components -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 0.85$ psi-sec

$m = 150 \text{ lb/ft}^2 = 1.04 \text{ lb/in}^2$

$V_{max} = [(0.85)(386.4)] / (1.04) = 316 \text{ in/sec} = \underline{26 \text{ ft/sec}}$

Surface 5: Cemesto® roof

Solid component -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 0.94$ psi-sec

$m = 4.7 \text{ lb/ft}^2 = 0.033 \text{ lb/in}^2$

$V_{max} = [(0.94)(386.4)] / (0.033) = 11{,}007 \text{ in/sec} = \underline{917 \text{ ft/sec}}$

Surface 6: Steel joist

Use Equation (14) or (15) to calculate V_{max}, as for a steel beam.

Assume the steel joist is composed of double 2" x 2" x 1/4" angles along the top and bottom chord. Use the weight per unit length estimated as 2.5 times the weight per unit length for a double angle to account for the double angles at the top and bottom chord and the web members.

So	i_T	=	0.26 psi-sec
	T	=	beam material toughness = 12,000 lb-in/in^3 (assuming A36 steel)
	L	=	beam length = 20 ft = 240 in
	b	=	loaded width
		=	4 in (width of top double angle for the joist)
	L'	=	2 L/b = 2 (240)/4 = 120 in
	A	=	2(1.88 in^2) = 3.76 in^2 (from AISC Steel Manual)
	w	=	6.38 lb/ft for a double angle so use w = 2.5 (6.38) = 15.95 lb/ft = 1.33 lb/in
	g	=	gravity constant = 386.4 in/sec^2
	ρ	=	w/Ag = 1.33/[(3.76)(386.4)] = 0.00092 lb-sec^2/in^4

First check

$$(i_T L'^{0.3} b)/((\rho T)^{1/2} A)$$

$$= [(0.26)(120)^{0.3}(4)]/[[(.00092)(12000)]^{1/2}(3.76)]$$

$$= (4.38)/(12.5) = 0.35$$

Since $0.35 \leq 9.0$

$$V_{max} = [T/\rho]^{1/2}[-0.41 + 0.41\ (i_T L'^{0.3} b)/((\rho T)^{1/2} A)]$$

$$V_{max} = [12000/.00092]^{1/2}\ [-0.41 + 0.41\ (0.35)]$$

V_{max} = -962 in/sec ⇒ <u>the joist does not fail, no debris</u>

<u>Surface 7</u>: Hollow steel door

Calculate the door velocity as

$$V_{max} = i_T / m$$

i_T = 0.82 psi-sec

m = 5.6 lb/ft^2 = 0.039 lb/in^2

V_{max} = [(0.82)(386.4)] / (0.039) = 8124 in/sec = <u>677 ft/sec</u>

<u>Step 4D:</u> Calculate the average velocity and velocity standard deviation for each surface. Use Equations (16) and (17).

<u>Surfaces 1 and 2</u>: Reinforced concrete walls

V_{max} = 28 ft/sec

V_{avg} = (0.6)(28) = 17 ft/sec
V_{std} = (0.14)(28) = 3.9 ft/sec

Surfaces 3 and 4: Reinforced concrete walls

V_{max} = 26 ft/sec
V_{avg} = 0.6(26) = 16 ft/sec
V_{std} = 0.14(26) = 3.6 ft/sec

Surface 5: Cemesto® roof

V_{max} = 917 ft/sec
V_{avg} = 0.6(917) = 550 ft/sec
V_{std} = 0.14(917) = 128 ft/sec

Surface 6: Steel joist

No debris

Surface 7: Hollow steel door

V_{max} = 677 ft/sec (single run)

Step 5: Calculate the average debris weight for each component.

Surfaces 1 - 4: Reinforced concrete walls

Use Equation (19)

m_{avg} = 0.10 [(rebar spacing)^2(cover thickness)(density)]

Assume rebar spacing = 12 in = 1 ft
cover thickness = 2 in = 0.17 ft
density = 150 lb/ft^3

So $m_{avg} = 0.10(1)^2(0.17)(150) = \underline{2.6\text{ lb}}$

Surface 5: Cemesto® roof

Use Equation (20) for masonry with shell face thickness = thickness of panel

m_{avg} = $(M')[(\text{shell face thickness})^3(\text{density})]$

Use thickness = 1 9/16" = 0.13 ft

density = $(4.7\ lb/ft^2)/0.13\ ft = 36\ lb/ft^3$

Since V_{max} = 917 ft/sec > 120 ft/sec, use

M' = 10

So, $m_{avg} = 10(0.13)^3(36) =$ <u>0.8 lb</u>

<u>Surface 6</u>. Steel joist

No debris

<u>Surface 7</u>: Hollow steel door

Use the total door weight for m_{avg}

$m_{avg} = (5.6\ lb/ft^2)(3\ ft)(7\ ft) =$ <u>118 lb</u>

<u>Step 6:</u> <u>Determine effective destroyed weight of each component.</u>

<u>Surfaces 1 and 2</u>: Reinforced concrete walls with far-range loading

Use Equations (27)

V_{max} = 28 ft/sec < 45 ft/sec, so $T' = 0.05$

So, by Equation (25)

Total effective destroyed mass = (0.05)(12)(20)(1)(150)

= <u>1800 lb</u>

<u>Surfaces 3 and 4</u>: Reinforced concrete walls with far-range loading

By Equation (27)

V_{max} = 26 ft/sec < 45 ft/sec

So, $T' = 0.05$

Using Equation (25)

Total effective destroyed mass = (0.05)(12)(20)(1)(150)

= <u>1800 lb</u>

Surface 5: Cemesto$_g$ roof

Use Equation (28) for unreinforced masonry

V_{max} = 917 ft/sec ≥ 190 ft/sec

So, T' = 1.0

Total effective destroyed mass = (1.0)(20)(20)(0.13)(36)
= 1872 lb

Surface 6: Steel joist

No debris

Surface 7: Hollow steel door

Total effective destroyed mass = total door mass
= (5.6)(3)(7) = 118 lb

Step 7: Calculate the destroyed width, GRIDL, of each component except the steel joists and hollow steel door. Constant distributions are used for the joists and the door so it is like running single trajectories for them. No trajectory run will be made for the joist since no debris are produced in this example. The bin width for the door should equal the length of the wall.

Use Equation (30)

Surfaces 1 - 4: Reinforced concrete walls

GRIDL = $\sqrt{(4/\Pi)(1800)/(150)}$ = 3.9 ft

Surface 5: Cemesto$_e$ roof

GRIDL = $\sqrt{(4/\Pi)(1872)/(4.7)}$ = 22.5 but the total width of the roof is only 20 ft so use GRIDL = 20 ft

Surface 6: Steel joist

No debris

Surface 7: Hollow steel door

GRIDL makes no difference, this is a single fragment run. Just put in the wall width of 20 ft.

Step 8: Set up input files for MUDEMIMP and run the code for each component (or like components).

Copies of each input file are included here.

Surfaces 1 and 2: Reinforced concrete walls

```
1,1
5000,1800.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 2 -- SURFACES (1) AND (2)
FT          LBS          SEC          FT-LBS
MASS        EXPONENT           2.6
VELOCITY    NORMAL            17.         3.9
ANGLE       NORMAL             0.         1.3
COF         UNIFORM            1.0        2.0
KFACTOR     CONSTANT           1.0
END
1      150.
7      3.0
8      1.0
10     1.0
12      2.0
19    -3.9
```

Maximum cumulative hazardous distance = 33 ft

Maximum range = 33 ft

Surfaces 3 and 4: Reinforced concrete walls

```
1,1
5000,1800.,0,58.,'OUTPUT',14555568 0
EXAMPLE PROBLEM 2 -- SURFACES (3) AND (4)
FT        LBS       SEC        FT-LBS
MASS      EXPONENT         .2.6
VELOCITY  NORMAL           16.          3.6
ANGLE     NORMAL            0.          1.3
COF       UNIFORM          1.0          2.0
KFACTOR   CONSTANT         1.0
END
1     150.
7     3.0
8     1.0
10    1.0
12     2.0
19   -3.9
```

Maximum cumulative hazardous distance = 29 ft

Maximum range = 30 ft

Surface 5: Cemesto® roof

```
1,1
5000,1872.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 2 -- SURFACE (5)
FT        LBS       SEC       FT-LBS
MASS      EXPONENT        0.8
VELOCITY  NORMAL         550.       128.
ANGLE     NORMAL          85.       10.0
COF       CONSTANT        1.5
KFACTOR   CONSTANT        1.0
END
1     36.
7     2.0
8     1.0
10    0.13
12    12.0
19   -20.0
```

Maximum cumulative hazardous distance = 330 ft

Maximum range = 353 ft

Considering half the roof debris (file the same except total effective destroyed mass = 1872/2 = 936 lb), the maximum cumulative hazardous distance = 310 ft.

Maximum range = 353 ft

Surface 7: Hollow steel door

NOTE: Doors are treated like 2-dimensional breakup debris from masonry. The drag coefficient is input as 1.5. The "L" parameter (input item 10) equals the door thickness.

Door thickness = 2 in = 0.17 ft

Adjust the input density (input item 1) so that

(density)(width)(length)(thickness) = door weight

$\rho(3)(7)(0.17) = 118$ lb

$\rho = 33$ lb/ft^3

```
1,1
1,118.,0,58.,'OUTPUT',145555568.0
EXAMPLE PROBLEM 2 -- SURFACE 7 (DOOR)
FT        LBS        SEC        FT-LBS
MASS      CONSTANT         118.
VELOCITY  CONSTANT         677.
ANGLE     CONSTANT           0.
COF       CONSTANT          1.5
KFACTOR   CONSTANT          1.0
END
1   33.
7   2.0
8   1.0
10  0.17
12  2.0
19  -20.0
```

Maximum range = 808 ft

Step 9: Make siting recommendation based on results for each direction from the structure.

The wall facing that direction and half the roof debris should be considered in each direction. The steel joists did not break away, so no debris are contributed by the joists. The distance traveled by the door should be included in setting the siting distance in the direction out from Surface 1 (the front wall). Its distance is compared to the cumulative density of the wall and the density caused by half the roof debris in that direction. The door is not included in the density calculation.

Surface 1 or 2:

The maximum range of any of the wall debris is 33 ft. Multiplied by the 1.3 safety factor, this distance is 43 ft. The cumulative hazardous debris distance for half the roof debris is 310 ft. However, the door travels 808 ft, so the safe siting distance would have to be 808 ft. This suggests a significant reduction in the hazardous debris distance could be made if a barricade or maze were designed to stop the door. If the door is stopped, the cumulative hazardous debris distance would be 310 ft. (Cumulative densities less than 43 ft would be greater for the combination of wall and roof debris, but past 43 ft they will not change.) The 1.3 safety factor only applies to concrete or masonry debris distance.

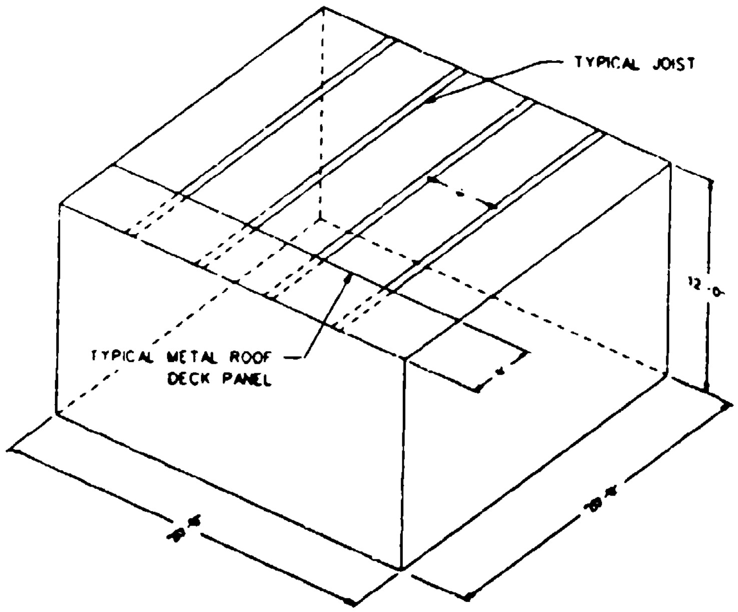
Surface 3 or 4:

The maximum distance of wall debris in the direction out from surface 3 or 4 is 30 ft. Multiplied by the 1.3 safety factor, this distance would be 39 ft. The cumulative hazardous debris distance for half the roof debris is 310 ft. Although the cumulative densities for distances less than 39 ft will increase when roof and wall debris are considered, the hazardous debris distance in the direction of Surface 3 or 4 is 310 ft. The 1.3 safety factor only applies to concrete or masonry debris distance, not the Cemesto® roof debris distance.

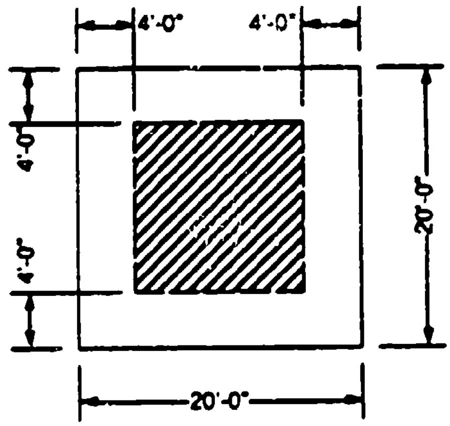
Example Problem No. 3

Step 1: Define the threat.

The building is 20 ft x 20 ft x 12 ft with three 12 inch thick reinforced concrete walls, one clay tile wall, and the roof of metal panels, 5-ply felt, and gravel. The metal panels have a 4 ft width and are 20 ft in length. They are supported by open web steel joists spaced at 4 ft on center. The weight/area of the metal panels is assumed to be 2 lb/ft^2. The weight/area of the built-up roof (felt and gravel) is assumed to be 6 lb/ft^2. The weight/area of the roof system is then 8 lb/ft^2.



A bare spherical charge equivalent to 250 lb TNT is assumed. It can be located anywhere within a designated HE area which has boundaries 4 feet from each wall as shown below. The minimum height off the floor is 2 feet.



For each surface, a charge location providing the highest total impulse, i_T, is selected, where i_T = the sum of the quasistatic impulse and the relevant shock impulse ($i_q + i_s'$). Figure A1 which follows should be used as a guideline to determine this worst case charge location for each surface. For this example, the worst case location for each surface is in a corner of the defined HE area nearest the surface, 2 feet off the floor.

The loaded surfaces for this example are defined below:

Surface 1	12 ft x 20 ft clay tile wall
Surface 2	12 ft x 20 ft reinforced concrete wall
Surface 3	12 ft x 20 ft reinforced concrete wall
Surface 4	12 ft x 20 ft reinforced concrete wall
Surface 5	20 ft x 20 ft metal panel roof with 5-ply felt and gravel
Surface 6	steel joist in roof

Step 2: Determine the vent areas and descriptions.

No open vent areas.

One covered vent area -- the roof (no door will be included in this example -- see Example Problem No. 2 for door calculations)

Covered vent area = (20)(20) = 400 ft^2

Vent perimeter = 4(20) = 80 ft

Weight per unit area of roof (metal panels, 5-ply felt, and gravel)
= 2 lb/ft^2 + 6 lb/ft^2 = 8 lb/ft^2
(No snow load is assumed for this example. The weight/area of the roof is the sum of the weight/areas of the metal panels and the felt and gravel.)

Step 3: Calculate the impulse load on each component.

Step 3A: Determine the shock impulse on each component.

Since a worst case charge location for each wall surface is in one of the closest corners of the HE area to the wall and the reinforced concrete walls are all 20 ft x 12 ft, the shock load for Surfaces 2 - 4 in this example will be identical.

Surface 1: 12 ft x 20 ft clay tile wall

Wall is a brittle material without significant strength

$R/W^{1/3} = 4/(250)^{1/3} = 0.63\ ft/lb^{1/3}$

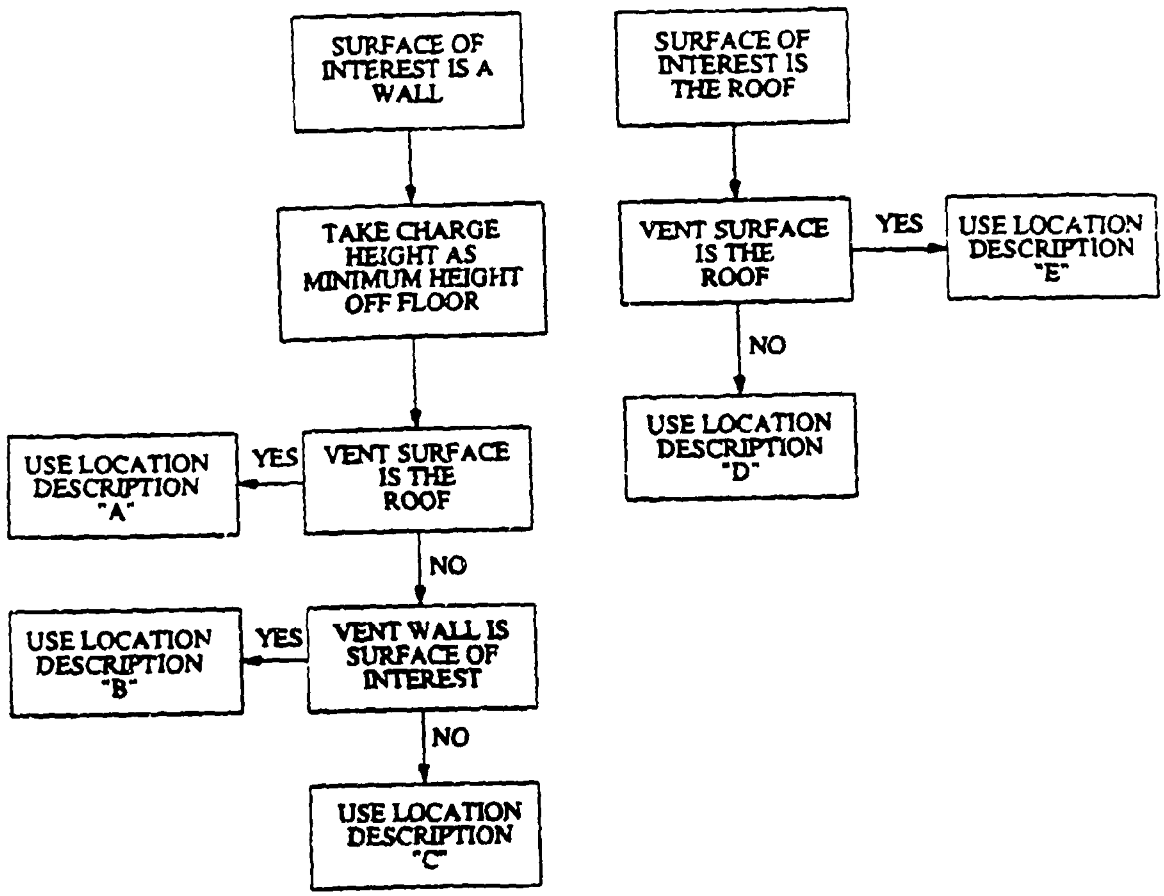
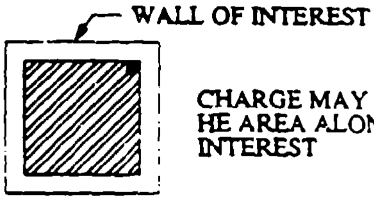


Figure A1. Selection of Charge Location for Worst Case Load

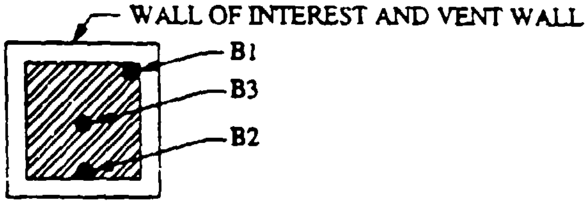
"A" -



CHARGE MAY BE PLACED IN EITHER CORNER OF DESIGNATED HE AREA ALONG BOUNDARY NEAREST WALL OF INTEREST

<u>HORIZONTAL PLANE AT MINIMUM CHARGE HEIGHT</u>

"B" -



<u>HORIZONTAL PLANE AT MINIMUM CHARGE HEIGHT</u>

IN ORDER TO OBTAIN THE WORST CASE DEBRIS HARZARD, THE MAXIMUM COMBINED QUASISTATIC AND SHOCK IMPULSE IS DESIRED. THE SHOCK IMPULSE INCREASES AND THE QUASISTATIC IMPULSE DECREASES WITH DECREASING STANDOFF. THE OPPOSITE IS TRUE FOR INCREASING STANDOFF. THEREFORE THE WORST CASE CHARGE LOCATION IS NOT INHERENTLY CLEAR. IN GENERAL THE FOLLOWING THREE LOCATIONS SHOULD BE INVESTIGATED.

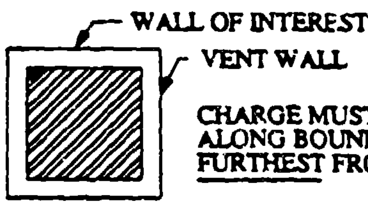
B1 - THE CHARGE POSITION FOR MAXIMUM SHOCK IMPULSE ON WALL

B2 - THE CHARGE POSITION FOR MAXIMUM QUASISTATIC IMPULSE ON THE WALL

B3 - AN INTERMEDIATE POSITION

EXPERIENCE MAY PRECLUDE THE NEED TO INVESTIGATE ALL THREE POSITIONS.

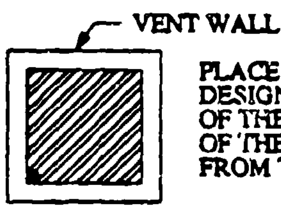
"C" -



CHARGE MUST BE PLACED IN CORNER OF DESIGNATED HE AREA ALONG BOUNDARY CLOSEST TO WALL OF INTEREST AND <u>FURTHEST</u> FROM VENT WALL.

<u>HORIZONTAL PLANE AT MINIMUM CHARGE HEIGHT</u>

"D" -

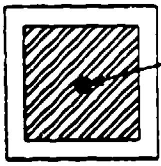


PLACE CHARGE AT MAXIMUM STANDOFF FROM FLOOR WITHIN DESIGNATED HE VOLUME. THIS DEFINES THE HORIZONTAL PLANE OF THE CHARGE. PLACE CHARGE IN THE CORNER (OR CORNERS) OF THE DESIGNATED HE BOUNDARY IN THIS PLANE FURTHEST FROM THE VENT SURFACE.

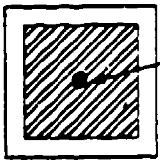
<u>HORIZONTAL PLANE AT MAXIMUM CHARGE HEIGHT</u>

Figure A1. Selection of Charge Location for Worst Case Load (continued)

"E" -



HORIZONTAL PLANE AT MINIMUM CHARGE HEIGHT



HORIZONTAL PLANE AT MIDHEIGHT OF DESIGNATED HE VOLUME

THIS IS SIMILAR TO CASE B SINCE THE VENT SURFACE IS ALSO THE SURFACE OF INTEREST. IN GENERAL THE FOLLOWING THREE CASES SHOULD BE CONSIDERED.

E1 - THE POSITION FOR MAXIMUM SHOCK IMPULSE ON THE ROOF (SAME POSITION AS LOCATION D)

E2 - THE POSITION FOR MAXIMUM QUASISTATIC IMPULSE ON THE ROOF

E3 - AN INTERMEDIATE POSITION

EXPERIENCE MAY PRECLUDE THE NEED TO INVESTIGATE ALL THREE POSITIONS.

Figure A1. Selection of Charge Location for Worst Case Load (continued)

It is a close-in load, but for both loading realms, you use the SHOCK code to get the impulse and duration at a point opposite the charge.

$R/W^{1/3} < 2.5$, so no multiplication factor will be applied to the impulse from SHOCK.

W = 250 lb

Distance to blast surface = 4 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 16 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Coordinates for point load = (16,2)

Shock impulse i_s for Surface 1 = 5.5 psi-sec

duration = 0.00065 sec

Surfaces 2 - 4: 12 ft x 20 ft reinforced concrete walls

Walls are brittle materials with significant strength

$R/W^{1/3} = 4/(250)^{1/3} = 0.63$ ft/lb$^{1/3}$

Since $0.5 < 0.63 < 1.0$, it is a close-in load.

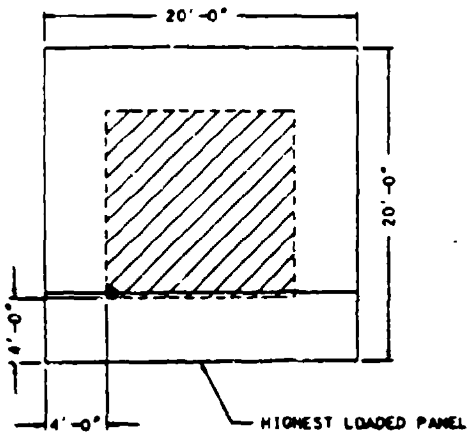
Use the SHOCK code to calculate the impulse and duration at a point on the component opposite the charge. Since the charge location for analyzing each wall will be the same as for Surface 1 and the SHOCK code is used in the same manner for close-in loads, the shock impulse i_s for Surfaces 2 - 4 = 5.5 psi-sec

duration = 0.00065 sec

Surface 5: 20 ft x 20 ft metal roof

Since the debris from the metal panels are expected to travel farther than debris from the 5-ply felt or gravel, we will only consider the load on the metal panels. Use the SHOCK code to get the average impulse over the panel with the highest loading.

The charge location will be in a corner of the HE area, 2 feet from the floor as shown.



Top View

The metal panel with the highest loading will be the panel directly above the charge, next to the sidewall. Use the reduced surface option of the SHOCK code for the area of this panel.

W = 250 lb

Distance to blast surface = 10 ft

Width of blast surface = 20 ft

Height of blast surface = 20 ft

Horizontal distance from reflecting surface 2 = 4 ft (sidewall)

Vertical distance from reflecting surface 1 = 16 ft (back wall)

4 reflecting surfaces

Average load on reduced surface of panel

Coordinates of upper left corner = (0,20)

Coordinates of lower right corner = (20,16)

Shock impulse i_s for Surface 5 = <u>1.3 psi-sec</u>

<u>Surface 6</u>: Steel joist in roof

Joist is a ductile material (like a steel beam)

Use the SHOCK code to get the average impulse over the loaded width of the joist with the highest loading. Based on the assumed joist dimensions, this width is 4 inches.

W = 250 lb

Distance to blast surface = 10 ft

Width of blast surface = 20 ft

Height of blast surface = 20 ft

Horizontal distance from reflecting surface 2 = 4 ft (sidewall)

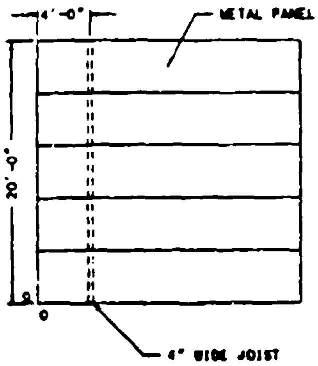
Vertical distance from reflecting surface 1 = 16 ft (back wall)

4 reflecting surfaces

Average load on reduced surface of joist

Coordinates of upper left corner = (3.83,20)

Coordinates of lower right corner = (4.17,0)



Roof as Loaded Surface -- Joist Surface as Reduced Surface for SHOCK Code

Shock impulse i_s for Surface 6 = <u>1.4 psi-sec</u>

<u>Step 3B</u>: Determine the quasistatic impulse on each component.

<u>Surface 1</u>: 12 ft x 20 ft clay tile wall

Brittle material without significant strength

Close-in load $(R/W^{1/3} = 4/(250)^{1/3} = 0.63\ ft/lb^{1/3} \le 1.0)$

Make two FRANG runs (see Step 3B 1) a) aa) - ac)).

FRANG Run No. 1

Vent panel = vent component = roof

W = 250 lb

Volume = (20)(20)(12) = 4800 ft^3

Covered vent area = 400 ft^2

Vent perimeter = 80 ft

Surface weight/area = 8 lb/ft^2

Shock impulse on panel = 1068 psi-msec
(SHOCK was rerun to get average load on full roof area.)

Uncovered vent area = 0

Recessed depth of panel = 0

Total quasistatic impulse = <u>1.6 psi-sec</u>

FRANG Run No. 2

Vent panel = local component area on Surface 1 opposite the charge

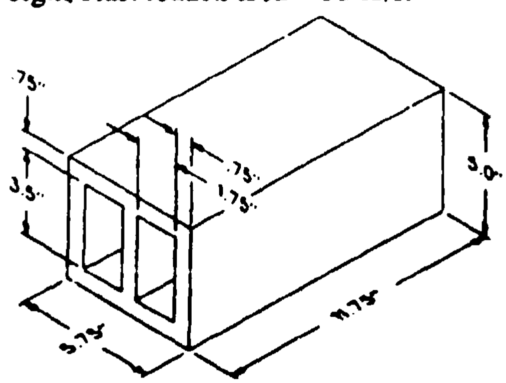
W = 250 lb

Volume = (20)(20)(12) = 4800 ft^3

Covered vent area = 2R x (R + 2) = 2(4)(6) = 48 ft^2
(have to adjust recommended 2R x 2R area due to charge height of 2 ft)

Vent perimeter = 2(2)(4) + 2(6) = 28 ft

Surface weight/blast loaded area = 33 lb/ft^2



Density of clay tile = 120 lb/ft^3

Weight = [(5.75)(5) - 2(1.75)(3.5)] (11.75)(1 ft^3/1728 in^3)(120 lb/ft^3)
= 13.5 lb

Weight/area = 13.5 lb/[(11.75)(5) in^2] (144 in^2/ft^2) = 33 lb/ft^2

Shock impulse on local area:

Run SHOCK with reduced area option for Surface 1

Coordinates of upper left corner = (12,6)

Coordinates of lower right corner = (20,0)

So shock impulse = 4538 psi-msec

Uncovered vent area = 0

Recessed depth of panel = 5.75 in = 0.48 ft
This recessed depth corresponds to the thickness of the wall. It is used here since the assumed locally failed portion of the wall must move through the thickness of the remaining portion of the wall before venting will occur.

Quasistatic impulse at critical vent time = 0.87 psi-sec

Use the lesser of quasistatic impulse from the two FRANG runs.

i_q = 0.87 psi-sec for Surface 1

Surfaces 2 - 4: 12 ft x 20 ft reinforced concrete walls

Brittle material with significant strength

Close-in load $(R/W^{1/3} = 4/(250)^{1/3} = 0.63 \text{ ft/lb}^{1/3} \leq 1.0)$

Make two FRANG runs (see Step 3B 1) a) aa) - ac)).

The first FRANG run is the same as FRANG Run No. 1 for Surface 1.

i_q = 1.6 psi-sec

FRANG Run No. 2 for Surfaces 2 - 4

Vent panel = local component area on Surface 2, 3, or 4 opposite the charge

W = 250 lb

Volume = (20)(20)(12) = 4800 ft^3

Covered vent area = 2R x (R + 2) = 2(4)(6) = 48 ft^2
(have to adjust recommended 2R x 2R area due to charge height of 2 ft)

Vent perimeter = 2(2)(4) + 2(6) = 28 ft

Surface weight/area = (150 lb/ft^3)(1 ft) = 150 lb/ft^2

Shock impulse on local area:

Run SHOCK with reduced area option for wall 2, 3, or 4

Coordinates of upper left corner = (12,6)

Coordinates of lower right corner = (20,0)

Shock impulse = 4538 psi-msec (same SHOCK run as local load on Surface 1)

Uncovered vent area = 0

Recessed depth of panel = 1 ft
The recessed depth of 1 ft is used here since the assumed locally failed portion of the wall must move through the thickness of the remaining portion of the wall before venting will occur.

Quasistatic impulse at critical vent time = 3.7 psi-sec

Use the lesser of quasistatic impulse from the two FRANG runs.

i_q = 1.6 psi-sec for Surfaces 2 - 4

Surface 5: 20 ft x 20 ft metal panel roof

Ductile material

Calculate the impulse in the same manner as for a far-range load on a brittle material.

Run FRANG with vent panel = vent component = roof and use the impulse at the critical vent time, indicated by AMAX on the output. The run is the same as FRANG Run No. 1 for Surface 1, but we need to use the impulse at AMAX, so

i_q = 1.2 psi-sec for Surface 5

Surface 6: Steel joist in roof

This member is treated as a steel beam would be treated by the model.

i_q = 0.0 psi-sec

Step 4: Calculate the maximum debris velocity expected for each component.

Step 4A: Calculate the relevant shock impulse, i_s'

Surface 1: Clay tile wall

Brittle material without significant strength

Use the impulse and duration from SHOCK and the component minimum mass per unit area to calculate the reduction factor, R_f, from the curve fit for unreinforced masonry.

i_s = 5.5 psi-sec

duration = 0.00065 sec

minimum mass/area = mass/area of the sum of the solid portions through the thickness of the hollow tile where this value is a minimum

$= (120\ lb/ft^3)(ft^3/1728\ in^3)(3\ (0.75\ in))/386.4\ in/sec^2$

$= 0.0004\ lb\text{-}sec^2/in^3$

From Equation (5)

$R' = (i_s/m)(duration)$

$R' = (5.5\ psi\text{-}sec)/(0.0004\ lb\text{-}sec^2/in^3)\ (0.00065\ sec)$

$= 8.9$ in

Since $R' = 8.9 \geq 0.54$, $R_f = 1.0$ by Equation (6)

So, the relevant shock impulse for Surface 1 is

$i_s' = i_s/R_f = 5.5/1.0 = \underline{5.5 \text{ psi-sec}}$ from Equation (9)

Surfaces 2 - 4: Reinforced concrete walls

Brittle material with significant strength

Close-in load ($R/W^{1/3} = 0.63 \leq 1.0$)

Use the impulse and duration from SHOCK and the component mass per unit area and compressive strength to calculate the reduction factor, R_f, from the curve fit for reinforced concrete.

From Equation (3)

$$R' = (i_s/m)(\text{duration})^{0.67}/(f'_c)^{0.5}$$

where $i_s = 5.5$ psi-sec

$m = 150 \text{ lb/ft}^2 = 1.04 \text{ lb/in}^2$

duration = 0.00065 sec

$f'_c = 3000$ psi (assumed value)

$R' = (5.5 \text{ psi-sec})/(1.04 \text{ lb/in}^2)(386.4 \text{ in/sec}^2)(0.00065 \text{ sec})^{0.67}/(3000)^{0.5}$

$R' = 0.27 \text{ in}^2/(\text{sec}^{0.33} \text{ lb}^{0.5})$

From Equation (4), for $R' = 0.27 \geq 0.084$

$$R_f = 1.0$$

So, by Equation (7),

$i_s' = i_s/R_f = 5.5/1.0 = \underline{5.5 \text{ psi-sec}}$ for Surfaces 2 - 4

Surface 5: Metal panel roof

From Equation (10) for ductile material

$i_s' = i_s = \underline{1.3 \text{ psi-sec}}$

Surface 6: Steel joist in roof

From Equation (10) for ductile material

$i_s' = i_s = \underline{1.4 \text{ psi-sec}}$

Step 4B: Calculate the total relevant impulse, i_T for each surface.

Use Equation (11)

$$i_T = i_q + i'_s$$

Surface 1: Clay tile wall

$$i_T = 0.87 + 5.5 = \underline{6.4 \text{ psi-sec}}$$

Surfaces 2 - 4: Reinforced concrete walls

$$i_T = 1.6 + 5.5 = \underline{7.1 \text{ psi-sec}}$$

Surface 5: Metal panel roof

$$i_T = 1.2 + 1.3 = \underline{2.5 \text{ psi-sec}}$$

Surface 6: Steel joist

$$i_T = 0.0 + 1.4 = \underline{1.4 \text{ psi-sec}}$$

Step 4C: Calculate the maximum debris velocity, V_{max}, for each surface.

Surface 1: Clay tile wall

Hollow component -- use Equation (13)

$$V_{max} = i_T / m'$$

where m' = minimum mass per unit area

$= (120 \text{ lb/ft}^3)(\text{ft}^3/1728 \text{ in}^3)(3\ (0.75 \text{ in}))/386.4 \text{ in/sec}^2$

$= 0.0004 \text{ lb-sec}^2/\text{in}^3$

$i_T = 6.4$ psi-sec

$$V_{max} = 6.4/0.0004 = 16000 \text{ in/sec} = \underline{1333 \text{ ft/sec}}$$

NOTE: This velocity exceeds the model limit of 1000 ft/sec. We will proceed to get a hazardous distance, noting we are going beyond data verified model results.

Surfaces 2 - 4: Reinforced concrete walls

Solid components -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 7.1$ psi-sec

$m = 150 \text{ lb/ft}^2 = 1.04 \text{ lb/in}^2$

$V_{max} = [(7.1)(386.4)] / (1.04) = 2638$ in/sec = 220 ft/sec

Surface 5: Metal panel from roof

Solid component -- use Equation (12)

$V_{max} = i_T / m$

$i_T = 2.5$ psi-sec

$m = 8 \text{ lb/ft}^2 = 0.056 \text{ lb/in}^2$ (including mass of felt and gravel)

$V_{max} = [(2.5)(386.4)] / (0.056) = 17{,}250$ in/sec = 1438 ft/sec

This velocity exceeds 1000 ft/sec, but higher velcocities were observed in tests using scaled charge weights less than 250 lb. So the velocity is acceptable for use with the model for metal panels if the charge weight does not exceed 250 lb.

Surface 6: Steel joist

Use Equation (14) or (15) to calculate V_{max}, as for a steel beam.

Assume the steel joist is composed of double 2" x 2" x 1/4" angles along the top and bottom chord. Use the weight per unit length estimated as 2.5 times the weight per unit length for a double angle to account for the double angles at the top and bottom chord and the web members.

So	i_T	=	1.4 psi-sec
	T	=	beam material toughness = 12,000 lb-in/in³ (assuming A36 steel)
	L	=	beam length = 20 ft = 240 in
	b	=	loaded width
		=	4 in (width of top double angle for the joist)
	L′	=	2 L/b = 2 (240)/4 = 120 in
	A	=	2(1.88 in²) = 3.76 in² (from AISC Steel Manual)
	w	=	6.38 lb/ft for a double angle so use w = 2.5 (6.38) = 15.95 lb/ft = 1.33 lb/in

g = gravity constant = 386.4 in/sec^2

ρ = $w/Ag = 1.33/[(3.76)(386.4)] = 0.00092$ lb-sec^2/in^4

First check

$(i_T L^{-0.3} b)/((\rho T)^{1/2} A)$

$= [(1.4)(120)^{0.3}(4)]/[[(.00092)(12000)]^{1/2}(3.76)]$

$= (23.5)/(12.5) = 1.9$

Since $1.9 \leq 9.0$

$V_{max} = [T/\rho]^{1/2}[-0.41 + 0.41\ (i_T L^{-0.3} b)/((\rho T)^{1/2} A)]$

$V_{max} = [12000/.00092]^{1/2}\ [-0.41 + 0.41\ (1.9)]$

V_{max} = 1333 in/sec = <u>111 ft/sec</u>

<u>Step 4D:</u> Calculate the average velocity and velocity standard deviation for each surface. Use Equations (16) and (17).

<u>Surface 1</u>: Clay tile wall

V_{max} = 1333 ft/sec

V_{avg} = (0.6)(1333) = 800 ft/sec

V_{std} = (0.14)(1333) = 187 ft/sec

<u>Surfaces 2 - 4</u>: Reinforced concrete walls

V_{max} = 220 ft/sec

V_{avg} = 0.6(220) = 132 ft/sec

V_{std} = 0.14(220) = 31 ft/sec

<u>Surface 5</u>: Metal panel from roof

V_{max} = 1438 ft/sec

V_{avg} = 0.6(1438) = 863 ft/sec

V_{std} = 0.14(1438) = 201 ft/sec

<u>Surface 6</u>: Steel joist

V_{max} = 111 ft/sec (for single run)

Step 5: Calculate the average debris weight for each component.

Surface 1: Clay tile wall

Use Equations (20) and (21) for masonry

$m_{avg} = M' [(\text{shell face thickness})^3 (\text{density})]$

where $M' = 10$ for $V_{max} = 1333 \geq 120$ ft/sec

shell face thickness = 0.75 in = 0.0625 ft

density = 120 lb/ft^3

$m_{avg} = 10 (0.0625)^3 (120) =$ 0.29 lb

Surfaces 2 - 4: Reinforced concrete walls

Use Equation (19)

$m_{avg} = 0.10 [(\text{rebar spacing})^2(\text{cover thickness})(\text{density})]$

Assume rebar spacing = 12 in = 1 ft

cover thickness = 2 in = 0.17 ft

density = 150 lb/ft^3

So $m_{avg} = 0.10(1)^2(0.17)(150) =$ 2.6 lb

Surface 5: Metal panel roof

Use Equations (23) and (24)

The mass will be uniformly distributed between

m_{min} = one-quarter of the total panel mass

and

m_{max} = total panel mass

$m_{max} = (4 \text{ ft})(20 \text{ ft})(2 \text{ lb/ft}^2) =$ 160 lb

$m_{min} = 0.25 (160 \text{ lb}) =$ 40 lb

Surface 6: Steel joist

Use Equation (22)

m = total joist mass = (15.95 lb/ft) (20 ft) = 319 lb

Step 6: Determine effective destroyed weight of each component.

Surface 1: Clay tile wall

From Equations (28) for unreinforced masonry

$V_{max} = 1333 \geq 190$ ft/sec

So, $T' = 1.0$

Total effective destroyed mass $= (1.0)(12)(20)(33)$

$= \underline{7920 \text{ lb}}$

where the wall is 20 ft x 12 ft and the weight/blast loaded area of the tiles is 33 lb/ft^2

Surfaces 2 - 4: Reinforced concrete walls with close-in loading

By Equation (26)

V_s = velocity from shock impulse alone

$V_s = i_s'/m = (5.5)(386.4)/1.04 = 2043$ in/sec $= 170$ ft/sec

Since $45 < 170 \leq 353$ ft/sec,

$T' = 0.00308\, V_s - 0.089$

$T' = 0.00308(170) - 0.089 = 0.43$

Total effective destroyed mass $= (0.43)(12)(20)(1)(150)$

$= \underline{15{,}480 \text{ lb}}$

Surface 5: Metal panel roof

$T' = 1.0$ from Equation (29)

Total effective destroyed mass $= (1.0)(4)(20)(2 \text{ lb/ft}^2)(5 \text{ panels}) = \underline{800 \text{ lb}}$

Surface 6: Steel joist

Use Equation (29) for beams, $T' = 1.0$

Total effective destroyed mass = mass of one joist = $\underline{319 \text{ lb}}$

Step 7: Calculate the destroyed width, GRIDL, of each component except the steel joists. Constant distributions are used for the joists so it is like running single trajectories for them.

Use Equation (30)

Surface 1: Clay tile wall

GRIDL = $\sqrt{(4/\Pi)(7920)/(33)}$ = 17.5 ft

Surfaces 2 - 4: Reinforced concrete walls

GRIDL = $\sqrt{(4/\Pi)(15{,}480)/(150)}$ = 11.5 ft

Surface 5: Metal panel roof

GRIDL = $\sqrt{(4/\Pi)(800)/(2)}$ = 22.6 but the total width of the roof is only 20 ft so use GRIDL = 20 ft

Surface 6: Steel joist

Use the roof width. GRIDL = 20 ft

Step 8: Set up input files for MUDEMIMP and run the code for each component (or like components).

Copies of each input file are included on the following pages.

Surface 1: Clay tile wall

```
1,1
5000,7620.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 3 -- SURFACE 1
FT        LBS       SEC       FT-LBS
MASS      EXPONENT        0.29
VELOCITY  NORMAL          800.       187.
ANGLE     NORMAL            0.         1.3
COF       CONSTANT          1.5
KFACTOR   CONSTANT          1.0
END
1    120.
7    2.0
8    1.0
10   0.0625
12    2.0
19  -17.5
```

Maximum cumulative hazardous distance = 1654 ft

Maximum range = 1773 ft

Surfaces 2 - 4: Reinforced concrete walls

```
1,1
5000,15480.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 3 -- SURFACES 2 - 4
FT          LBS          SEC         FT-LBS
MASS        EXPONENT              2.6
VELOCITY    NORMAL              132.             31.
ANGLE       NORMAL                0.             1.3
COF         UNIFORM               1.0            2.0
KFACTOR     CONSTANT              1.0
END
1      150.
7      3.0
8      1.0
10     1.0
12      2.0
19   -11.5
```

Maximum cumulative hazardous distance = 926 ft

Maximum range = 974 ft

Surface 5: Metal panel roof

```
1,1
5000,800.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 3 -- SURFACE 5
FT        LBS        SEC       FT-LBS
MASS      UNIFORM          40.        160.
VELOCITY  NORMAL          863.        201.
ANGLE     NORMAL           90.        10.0
COF       CONSTANT         1.5
KFACTOR   CONSTANT         1.0
END
1     490.
7     2.0
8     1.0
10    0.004
12    12.0
19   -20.0
```

Maximum cumulative hazardous distance = 90 ft

Maximum range = 264 ft

Note on the selection of "L" (input item 10) for the corrugated metal panels:

The code internally calculates area as

A = mass/((density)(L))

So, L = mass/ρA

For these panels, mass = 160 lb

$$A = 4(20) = 80\ ft^2$$

$$\rho = 490\ lb/ft^3$$

$$L = (160) / ((490)(80)) = 0.004\ ft$$

Considering half the roof debris (file the same except total effective destroyed mass = 800/2 = 400 lb), the maximum cumulative hazardous distance = 50 ft.

Maximum range = 264 ft

Surface 6: Steel joist in roof

```
1,1
1,319.,0,58.,'OUTPUT',145555568.0
EXAMPLE PROBLEM 3 -- SURFACE 6
FT         LBS        SEC        FT-LBS
MASS       CONSTANT        319.
VELOCITY   CONSTANT        111.
ANGLE      CONSTANT         90.
COF        CONSTANT         1.8
KFACTOR    CONSTANT         1.0
END
1  490.
7  2.0
8  1.0
10 0.2
12 12.0
19 -20.0
```

A note on the selection of "L" (input item 10) for a steel joist (or beam, etc.): It is difficult to estimate what area will be presented in flight. We will try to account for an average area by taking an area as

$$A = 0.5\ (\text{width of double angle})(\text{joist length})$$

$$A = 0.5\ (4\ \text{in})(\text{ft}/12\ \text{in})(20\text{ft}) = 3.3\ \text{ft}^2$$

The code internally determines area as

$$A = \text{mass}/((\text{density})(L))$$

So, use $L = \text{mass}/\rho A = 319\ \text{lb}/[(490\ \text{lb/ft}^3)(3.3\ \text{ft}^2)] = 0.2\ \text{ft}$

Maximum distance = 12.5 ft

Step 9: Make siting recommendation based on results for each direction from the structure.

The wall facing that direction and half the roof debris should be considered in each direction.

Surface 1:

The maximum cumulative hazardous debris distance for the clay tile debris is 1654 ft. The maximum range traveled by any of the roof debris (metal panels or steel joists) is 264 ft, so the roof debris do not increase the hazardous debris distance of the wall debris. Applying the 1.3 safety factor for concrete and masonry debris, the siting distance is then (1654)(1.3) = 2150 ft.

Application of the model in this paper will often permit siting distance reductions from the broad-ranged criteria (670 or 1250 feet) now in Reference 1. However, in some cases predicted hazardous debris distances will even exceed the default distance criteria of Reference 1. In these cases, and because the model in this paper is considered safety conservative, the default criteria may be used.

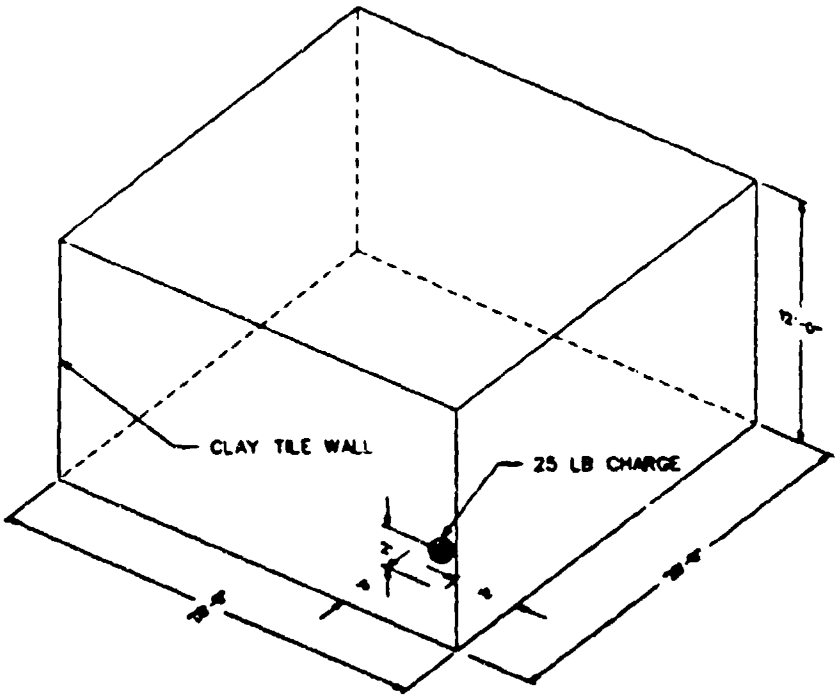
Surfaces 2 - 4:

The cumulative hazardous debris distance from the reinforced concrete wall debris is 926 ft. The maximum distance traveled by any roof debris (metal panels or steel joists) is 264 ft, so the roof debris do not increase the hazardous debris distance of the wall debris. Applying the 1.3 safety factor for reinforced concrete and masonry debris, the siting distance is (926)(1.3) = 1204 ft.

Example Problem No. 4

Step 1: Define the threat.

The building is 20 ft x 20 ft x 12 ft with three very thick reinforced concrete walls designed not to fail, one clay tile wall, and a reinforced concrete roof designed not to fail. The charge of 25 lb is located 3 feet from the clay tile wall, 3 feet from one reinforced concrete wall, and 2 feet from the floor. No door calculations will be done in this example. See Example Problem No. 2 for door calculations.



Since the three reinforced concrete walls and the reinforced concrete roof have been designed to withstand the effects of the 25 lb charge (no debris will result), the only surface to be examined is the clay tile wall, Surface 1.

Step 2: Determine the vent areas and descriptions.

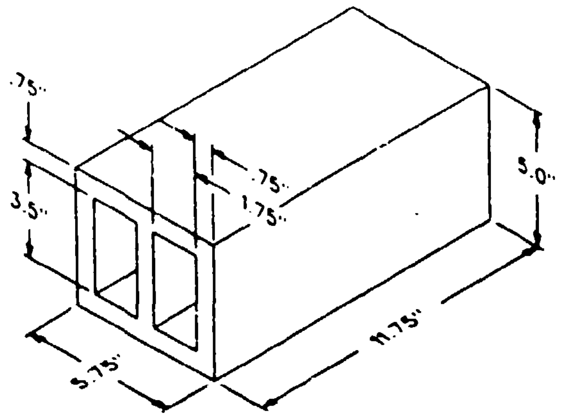
No open vent areas.

One covered vent area -- the clay tile wall in this case

Covered vent area = (20)(12) = 240 ft^2

Vent perimeter = 2(12) + 2(20) = 64 ft

Weight per unit blast loaded area of wall = 33 lb/ft^2



Density of clay tile = 120 lb/ft^3

Weight $= [(5.75)(5) - 2(1.75)(3.5)]\ (11.75)(1\ ft^3/1728\ in^3)(120\ lb/ft^3)$

$= 13.5$ lb

Weight/area $= 13.5\ lb/[(11.75)(5)\ in^2]\ (144\ in^2/ft^2) = 33\ lb/ft^2$

Step 3: Calculate the impulse load on each component.

Step 3A: Determine the shock impulse on the clay tile wall.

Surface 1: 12 ft x 20 ft clay tile wall

Wall is a brittle material without significant strength

$R/W^{1/3} = 3/(25)^{1/3} = 1.03\ ft/lb^{1/3}$

For both close-in and far-range loads, use the SHOCK code to get the impulse and duration at a point opposite the charge.

$R/W^{1/3} < 2.5$, so no multiplication factor will be applied to the impulse from SHOCK.

W = 25 lb

Distance to blast surface = 3 ft

Width of blast surface = 20 ft

Height of blast surface = 12 ft

Horizontal distance from left side wall = 3 ft

Vertical distance from floor = 2 ft

4 reflecting surfaces

Coordinates for point load = (3,2)

Shock impulse i_s for Surface 1 = <u>1.05 psi-sec</u>

duration = <u>0.0003 sec</u>

<u>Step 3B</u>: Determine the quasistatic impulse for the clay tile wall.

<u>Surface 1</u>: 12 ft x 20 ft clay tile wall

Brittle material without significant strength

Far-range load ($R/W^{1/3} = 3/(25)^{1/3} = 1.03$ ft/lb$^{1/3}$ > 1.0)

Run FRANG with the vent panel = vent component = clay tile wall.

Use the impulse at "AMAX" since the vent component is the component of interest.

W = 25 lb

Volume = (20)(20)(12) = 4800 ft^3

Covered vent area = 240 ft^2 from Step 2

Vent perimeter = 64 ft from Step 2

Surface weight/blast loaded area = 33 lb/ft^2

Shock impulse on panel = 318 psi-msec
(SHOCK was rerun to get average load on full wall area.)

Uncovered vent area = 0

Recessed depth of panel = 0

Quasistatic impulse at critical vent time = <u>1.2 psi-sec</u>

The load on this wall is very near the boundary of being a close-in load instead of a far-range load. If the load were considered close-in, the quasistatic impulse to be used would be 0.6 psi-sec. This corresponds to the impulse resulting from a local area of the wall venting before the whole wall vents. We will conservatively use the impulse of 1.2 psi-sec since this will result in greater velocities and distance.

Step 4: Calculate the maximum debris velocity expected for the clay tile wall debris.

Step 4A: Calculate the relevant shock impulse, i_s'

Surface 1: Clay tile wall

Brittle material without significant strength

Use the impulse and duration from SHOCK and the component minimum mass per unit area to calculate the reduction factor, R_f, from the curve fit for unreinforced masonry.

$i_s = 1.05$ psi-sec

duration = 0.0003 sec

minimum mass/area = mass/area of the sum of the solid portions through the thickness of the hollow tile where this value is a minimum

$= (120 \text{ lb/ft}^3)(\text{ft}^3/1728 \text{ in}^3)(3\ (0.75 \text{ in}))/386.4 \text{ in/sec}^2$

$= 0.0004 \text{ lb-sec}^2/\text{in}^3$

From Equation (5)

$R' = (i_s/m)(\text{duration})$

$R' = (1.05 \text{ psi-sec})/(0.0004 \text{ lb-sec}^2/\text{in}^3)\ (0.0003 \text{ sec})$

$= 0.79$ in

Since $R' = 0.79 \geq 0.54$, $R_f = 1.0$ by Equation (6)

So, the relevant shock impulse for Surface 1 is

$i_s' = i_s/R_f = 1.05/1.0 =$ 1.05 psi-sec from Equation (9)

Step 4B: Calculate the total relevant impulse, i_T.

Use Equation (11)

$$i_T = i_q + i_s'$$

Surface 1: Clay tile wall

$$i_T = 1.2 + 1.05 = 2.3 \text{ psi-sec}$$

Step 4C: Calculate the maximum debris velocity, V_{max}.

Surface 1: Clay tile wall

Hollow component -- use Equation (13)

$$V_{max} = i_T / m'$$

where m' = minimum mass per unit area

$= (120\ lb/ft^3)(ft^3/1728\ in^3)(3\ (0.75\ in))/386.4\ in/sec^2$

$= 0.0004\ lb\text{-}sec^2/in^3$

$i_T = 2.3$ psi-sec

$V_{max} = 2.3/0.0004 = 5750$ in/sec = 479 ft/sec

Step 4D: Calculate the average velocity and velocity standard deviation using Equations (16) and (17).

Surface 1: Clay tile wall

V_{max} = 479 ft/sec

V_{avg} = (0.6)(479) = 287 ft/sec

V_{std} = (0.14)(479) = 67 ft/sec

Step 5: Calculate the average debris weight.

Surface 1: Clay tile wall

Use Equations (20) and (21) for masonry

$m_{avg} = M'$ [(shell face thickness)^3 (density)]

where $M' = 10$ for $V_{max} = 479 \geq 120$ ft/sec

shell face thickness = 0.75 in = 0.0625 ft

density = 120 lb/ft^3

$m_{avg} = 10\ (0.0625)^3\ (120) =$ 0.29 lb

Step 6: Determine effective destroyed weight of the component using Equation (25).

Surface 1: Clay tile wall

From Equations (28) for unreinforced masonry

$V_{max} = 479 \geq 190$ ft/sec

So, $T' = 1.0$

Total effective destroyed mass = (1.0)(12)(20)(33)

= 7920 lb

where the wall is 20 ft x 12 ft and the weight/blast loaded area of the tiles is 33 lb/ft^2

Step 7: Calculate the destroyed width, GRIDL, of the component.

Use Equation (30)

Surface 1: Clay tile wall

$$\text{GRIDL} = \sqrt{(4/\Pi)(7920)/(33)} = 17.5 \text{ ft}$$

Step 8: Set up input file for MUDEMIMP and run the code to determine the hazardous debris distance for the clay tile wall.

A copy of the input file is included here.

Surface 1: Clay tile wall

```
1,1
5000,7920.,0,58.,'OUTPUT',14555568.0
EXAMPLE PROBLEM 4 -- SURFACE 1
FT          LBS          SEC          FT-LBS
MASS        EXPONENT          0.29
VELOCITY    NORMAL            287.          67.
ANGLE       NORMAL              0.          1.3
COF         CONSTANT           1.5
KFACTOR     CONSTANT           1.0
END
1     120.
7     2.0
8     1.0
10    0.0625
12     2.0
19   -17.5
```

Maximum cumulative hazardous distance = 709 ft

Maximum range = 714 ft

Step 9: Make siting recommendation based on results for each direction from the structure.

Siting distances in the directions of the three reinforced concrete walls will be set by blast criteria since these walls and the roof have been designed not to fail. The distance in the direction out from Surface 1, the clay tile wall, will be set by the cumulative hazardous debris distance of the debris from that wall.

Surface 1:

The maximum cumulative hazardous debris distance for the clay tile debris is 709 ft. Applying the 1.3 safety factor for concrete and masonry debris, the siting distance is then (709)(1.3) = 922 ft. The large distance results from a full contribution of quasistatic load on the clay tile wall since no other vents were considered. This distance exceeds the default distance of 670 ft (25 lb < 100 lb) due to the charge confinement.

Application of the model in this paper will often permit siting distance reductions from the broad-ranged criteria (670 or 1250 feet) now in Reference 1. However, in some cases predicted hazardous debris distances will even exceed the default distance criteria of Reference 1. In these cases, and because the model in this paper is considered safety conservative, the default criteria may be used.